DISSERTATION FROM THE
NORWEGIAN SCHOOL OF
SPORT SCIENCES
2019

Ola Eriksrud

Hand reach star excursion balance test

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OF SPORT SCIENCES

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ISBN 978-82-502-0572-7

No bird soars too high if he soars with his own wings

William Blake

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Acknowledgements

This thesis was undertaken at the Department of Physical Performance at the Norwegian School of Sport Sciences (NSSS), Oslo, Norway. From the original concept to its submission, it was a team effort. In fact, it is similar to the HSEBT, which is a team effort of joint movements contributing to the hand reach measurements.

To my advisors, Jan Cabri and Peter Federolf, thank you. In the darkest hours you never gave up on me. Your honest, positive (mostly) and constructive feedback often pulled me back to a focused path toward the submission of this thesis.

Without my creative and curious clinical friends and colleagues Jessica Parnevik Muth and Ali Ghelem the HSEBT would not have seen the light of day. You are brilliant clinicians and I hope this is just the beginning, as many ideas and thoughts have been discussed over the years. Thank you.

Thank you Jostein Hallen and Klavs Madsen and the Department of Physical Performance. Your support throughout the years has been invaluable. Jostein, thank you for believing in me and giving me the opportunity to take my own path. Not many would have the guts to do this, but you did. Thank you.

Thank you to all my colleagues at the department. You have all been a support whether you know it or not. It was a privilege to have the opportunity to ask questions within the department, ranging from statistical analyses to Matlab scripts. Specifically, thank you Olivier Seynnes, Jens Bojsen-Møller, Tormod Skogstad Nilsen, Live Luteberget, Marie Moltubakk, Øyvind Skattebo, May Grydeland and Øyvind Glørsen for your support.

Thank you to all the students that I have had the privilege to work with over the years, especially Fredrik Sæland, Patrick Anderson, Stavros Litsos and Eirik Andreassen for your dedication and contribution to the project. All of you have that quality of going above and beyond. This is an invaluable quality that you must never lose.

Thank you to Olympiatoppen and especially Morten Bråten, Lars Arne Andersen, Claude Lebreaux, Jane Paris, Gøran Paulsen, Thomas Haugen and Paul Andre Solberg. Your insights, curious questions and honest feedback have not only made this project better, but also made me a better coach and clinician. Also, my thanks to the Medical Department and Bjørn Fossan and Roald Bahr for giving me the opportunity to work clinically as a physiotherapist over the years.

Thank you to my colleagues in 1080 Motion. Your knowledge, creativity and dedication is source of true inspiration.

To all my mentors and heroes: David Tiberio, the brilliant biomechanics professor who introduced me to biomechanics and ever since has challenged my understanding of human movement. Gary Gray, since I first heard you speak in 1996, you have been a source inspiration on many levels in my personal and professional life, and you have encouraged me to challenge the status quo. Vern Gambetta, our conversations are few and far between, but the ones we have had I will cherish for the rest of my life. To my hero Alberto Minetti: some lectures are good, some are great; yours are truly a piece of art. Thank you for enlightening me.

To my family: You have paid the greatest price for this ego-trip. Without your support and understanding none of this would have been possible. Isak and Sofus, dad will now have more time practice his ninja skills in order to be a proper sparring partner, and to be the best basketball coach Gullkroken has ever seen. Annette, the glue of the household, this one is for you. Without you I would be poorer in so many ways. I love you.

Finally, to the rest of my family and friends: It is great to have people in my life who can put this project into a wider context.

Oslo, March, 2019

Ola Eriksrud

List of publications

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I. Eriksrud, O., Federolf, P., Sæland, F., Litsos, S. & Cabri J. (2017). Reliability and validity of the hand reach star excursion balance test. *Journal of Functional Morphology Kinesiology*, 2(3), 28. doi: 10.3390/jfmk2030028

II. Eriksrud, O., Federolf, P., Anderson, P. & Cabri, J. (2018). Hand reach star excursion balance test: an alternative test for dynamic postural control and functional mobility. *PLoS One*, May 8; 13(5). doi: 10.1371/journal.pone.0196813

III. Eriksrud, O., Sæland, F., Federolf, J. & Cabri, J. (2019). Functional mobility and dynamic postural control predict overhead handball throwing performance in elite female team handball players. *Journal of Sports Science and Medicine*, 18, 91-100.

IV. Eriksrud, O., Federolf, P. & Cabri, J. (2019). Influence of anthropometry, age, sex and activity level on the hand reach star excursion balance test. Manuscript in revision in *Frontiers in Psychology*.

Summary

Background

Different tests for dynamic postural control; i.e., the ability to maintain a stable base while completing a movement, are frequently used to assess functional and athletic performance. Current tests primarily target either the lower extremities or the trunk and the upper extremities. In addition, these tests have variable demands on functional mobility, which is defined as the combination of the range of motion (ROM) of multiple joints used to accomplish ecological tasks. Currently there are no tests of dynamic postural control that simultaneously impose three-dimensional mobility demands on the trunk, lower and upper extremities. The purpose of this thesis was to develop a new test of dynamic postural control to target these shortcomings and to establish 1) validity; 2) reliability; 3) the influence of potential covariates such as anthropometry, age, sex and level of physical activity; and 4) the influence on overhead athletic performance.

Methods

The thesis is based on four different research projects that used an observational design with a total of 222 participants; these projects represent the development of the hand reach star excursion balance tests (HSEBT). Standardized testing procedures were developed by a group of experts, based on: 1) starting position; 2) task; 3) measurement; and 4) ending position, which served as content validity. In study I, criterion-related and construct validity were explored. Specifically, the magnitudes of joint movements used to assume maximum HSEBT reach positions were quantified using motion capture (Qualisys Oqus 400 cameras, Qualisys AB, Gothenburg, Sweden) and compared to joint movements in the comparable star excursion balance test (SEBT) and normative ROM values. Criterion-related (concurrent) validity was established by comparing reach measurements calculated from motion capture data to those visually obtained using Bland Altman and correlational analysis. Construct validity was assessed by correlating outcome measurements (reach, composite scores and area calculations) from the HSEBT with the comparable SEBT. In study II, inter-rater and test-retest reliability was assessed from the outcome measurements of three experienced testers using intraclass correlation coefficients (ICC), with the calculation of stability measurements

(standard error or measurement and coefficient of variation) and minimal detectable change. The influence of anthropometry, age, sex and level of physical activity was explored in study III. Stepwise linear regression was used to determine the influence of these factors on reach measurements. Independent samples t-tests were used to determine between-group (age, sex and level of physical activity) differences with calculation of effect sizes and group difference comparisons to minimal detectable change values (study II). The influence of HSEBT reach measurements on athletic performance (overhead team handball throwing) in an elite female population was explored for both throwing velocity, calculated from motion capture data, and accuracy, via mean radial error calculated from video records, using Pearson correlational analysis.

Main results

The HSEBT elicited significantly greater joint movements than the SEBT in 18 out of 22 joint movement comparisons. The magnitude of these joint movements was comparable to the ranges of normative ROM values for 8 out of 22 joint movements. Excellent correlations were observed between visually observed and calculated reach measurements from motion capture data for 18 out of 20 tests ($r \geq 0.90$) with a shared variance that ranged from 81 to 97%. For the remaining two tests good correlations were observed (r = .79 and .89). The fixed biases observed (range = 2.2 to 12.8 cm, −6.0 to 11.2° and 23.7%) can be partially explained by the methods used to calculate reach measurements. Different composite and area scores for the HSEBT and SEBT had variable correlations (range r = .269 to .823), with a wider range of observed values for the individual reaches (range r = -.182 to .822). The strongest correlations were observed for the anterior composite, area and reach measurement comparisons (range r = .515 to .823). In Study II moderate to high test-retest reliability was observed for 19 out of 20 reaches (range ICC = 0.80 to 0.96). The inter-rater reliability was high for all reaches (range ICC = 0.90 to 0.98). Minimal detectable change values ranged from 0.9–7.9 cm and 4.7–7.2° for all reaches. Wingspan (study III) explained 34.6 and 11.7% of the variance of two HSEBT reaches. When normalized (% of wingspan) the same reaches were influenced by age, sex and level of physical activity with significant between-group differences, and moderate effect sizes (range d = .50 to .72). In addition, one non-normalized reach was influenced by age and level of physical activity (range d = .55 to

.75). HSEBT reach measurements are not correlated with throwing velocity (range r = -.530 to .395), but with mean radial error for some reaches (range r = .149 to .666) (study IV).

Conclusions

The HSEBT is a valid and reliable measure of dynamic postural control that measures different aspects of dynamic postural control compared to the SEBT, especially in the lateral and posterior directions. Greater joint movements of the lower extremity, trunk and shoulder joint are elicited by the HSEBT than the SEBT, making it a useful addition to tests of functional mobility. Reach specific normalization to wingspan is indicated, and age, sex and level of physical activity should be accounted for when performing between-individual and group comparisons for specific HSEBT reaches. No beneficial effect of increased HSEBT reach measurements on throwing performance could be established in elite female team handball players.

Sammendrag på norsk

Bakgrunn

Ulike tester for dynamisk postural kontroll brukes ofte til å vurdere fysisk og idrettslig prestasjonsevne. Nåværende tester er primært rettet mot enten underekstremitetene eller truncus sammen med overekstremitetene. I tillegg har disse testene ulike krav til funksjonell mobilitet, kombinasjonen av leddutslag (ROM) til flere ledd som sammen benyttes for å gjennomføre en oppgave eller bevegelse. Per i dag er det ingen tester for dynamisk postural kontroll som stiller samtidige krav til tredimensjonale leddutslag i truncus, over- og underekstremitetene. Formålet med denne avhandlingen var å utvikle en ny test for dynamisk postural kontroll for å dekke disse behovene og etablere 1) validitet; 2) reliabilitet; 3) hvordan antropometriske målinger, alder, kjønn og nivå av fysisk aktivitet påvirker utfallsmål; og 4) hvordan utfallsmål påvirker idrettslig prestasjonsevne (håndballkast).

Metode

Totalt deltok 222 forskningsdeltakere i utviklingen av hand reach star excursion balance test (HSEBT) i fire forskjellige forskningsprosjekter (studie I-IV). Standardiserte testprosedyrer ble utviklet av en gruppe eksperter basert på: 1) startstilling; 2) oppgave; 3) måling; og 4) sluttstilling som dannet innholdsvaliditeten til HSEBT. I studie I ble kriterie- og konstruktvaliditeten utforsket. Nærmere bestemt ble størrelsen og kombinasjonen av de ulike leddutslagene som ble benyttet for å oppnå maksimale HSEBT utfallsmål kvantifisert fra bevegelsesdata (Qualisys Oqus 400-kameraer, Qualisys AB, Göteborg, Sverige). Videre ble disse leddutslagene sammenlignet med de brukt for å oppnå maksimale star excursion balance test (SEBT) utfallsmål og med normative verdier. Kriterievaliditeten (samtidig validitet) ble etablert ved å sammenligne utfallsmål beregnet ut fra bevegelsesdata mot de som ble visuelt målt ved hjelp av Bland Altman og korrelasjonsanalyse. Konstruktvaliditeten ble vurdert ved å korrelere utfallsmål (individuelle tester, sammensatte scores og arealberegninger) fra HSEBT mot SEBT. I studie II ble inter-rater og test-retest reliabilitet etablert fra utfallsmålingene til tre erfarne testere ved bruk av intra-klasse korrelasjonskoeffisient (ICC), standardfeilen til målingen (SEM), variasjonskoeffisienten (CV) og minste reelle endring (MDC). Påvirkningen av antropometriske målinger, alder, kjønn og fysisk aktivitet på utfallsmålingene ble utforsket med en trinnvis lineær regresjon i studie III.

Videre ble gruppeforskjeller (alder, kjønn og ulike nivåer av fysisk aktivitet) analysert med uavhengig t-tester, beregning av effektstørrelser og sammenlignet med minste reelle endring (etablert studie II). HSEBT sin innflytelse på idrettslig prestasjonsevne (overarmskast i håndball hos kvinnelige elitespillere) ble utforsket for hastighet, beregnet fra bevegelsesdata, og nøyaktighet, mean radial error beregnet fra video, ved hjelp av Pearsons korrelasjonsanalyse.

Resultat

HSEBT fremkalte signifikant større leddutslag enn SEBT i 18 av de 22 leddbevegelsene som ble sammenlignet og størrelsen til disse var sammenlignbare med normative verdier for 8 av 22 leddutslag. Utmerkede korrelasjoner ble observert mellom visuelt observerte og kalkulerte utfallsmålinger fra bevegelsesdata for 18 av 20 tester (r ≥ 0.90), med en delt varians fra 81 til 97%. For de resterende to testene ble det observert gode korrelasjoner (variasjonsbredde r = .79 og .89). De observerte fikserte skjevhetene (variasjonsbredde 2.2 til 12.8 cm, -6.0 til 11.2° og 23.7%) mellom observerte og kalkulerte utfallsmål kan delvis forklares av de metodene som ble benyttet for å beregne utfallsmålene fra bevegelsesdata. De ulike sammensatte scorene og arealberegningene fra utfallsmålinger for HSEBT og SEBT hadde variable korrelasjoner (variasjonsbredde r = .269 til .823) hvor en bredere distribusjon ble observert for individuelle tester (variasjonsbredde r = -.182 til .822). De sterkeste korrelasjonene ble observert for de fremre sammensatte scorene, områdeberegningen og individuelle testene (variasjonsbredde r = .515 til .823). I studie II ble moderat til høy test-retest reliabilitet observert for 19 ut av 20 tester (variasjonsbredde ICC = 0.80 til 0.96). Inter-rater reliabiliteten var høy for alle testene (variasjonsbredde ICC = 0.90 til 0.98). Verdier for minimal reell endring varierte fra 0.9-7.9 cm og 4.7-7.2° for alle tester. Vingespenn forklarte 34.6 og 11.7% av variansen for to HSEBT tester (studie III). Etter normalisering (% av vingespenn) påvirket alder, kjønn og fysisk aktivitet de samme testene med signifikante forskjeller i utfallsmålene mellom gruppene med moderate effektstørrelser (variasjonsbredde *d* = .50 til .72). Videre ble en ikke-normalisert test påvirket av alder og nivå av fysisk aktivitet (variasjonsbredde *d* = .55 til .75). HSEBT tester korrelerer ikke med kasthastighet (variasjonsbredde r = -.530 til .395), men med mean radial error for noen tester (variasjonsbredde r = .149 til .666) (studie IV).

Konklusjon

HSEBT er en valid og reliabel test for dynamisk postural kontroll som måler andre aspekter av dynamisk postural kontroll enn SEBT, spesielt i de laterale og posteriore testene. Større leddutslag i underekstremitetene, truncus og skulderleddene er observert i HSEBT enn i SEBT. Dette gjør også HSEBT til et nyttig tillegg til tester av funksjonell mobilitet. Normalisering av noen tester til vingespenn er indikert, og alder, kjønn og fysisk aktivitet bør tas med i betraktningen når man skal sammenligne mellom individer og grupper. Ingen gunstig effekt av økte HSEBT utfallsmål på kastprestasjon i en populasjon av kvinnelige håndballspillere på elitenivå ble observert.

Abbreviations

4H3C – Four hops and three contacts

APSI – Anterior to posterior stability index

BOS – Base of support

CKCUEST – Closed kinetic chain upper extremity stability tests

COM – Center of mass

COP - Center of pressure

COG – Center of gravity

CV - Coefficient of variation

FMS – Functional movement screen

FRT – Functional reach test

DPSI – Dynamic postural stability index

HSEBT - Hand reach star excursion balance tests

ICC - Intraclass correlation coefficient

LOG – Line of gravity

LOS - Limits of stability

MDC - Minimal detectable change

MLSI – Medial to lateral stability index

ROM – Range of motion

SEBT - Star excursion balance test

SEM - Standard error of measurement

SFMA – Selective functional movement assessment

SRT - Seated reach test

TTS – Time to stabilization

VGRF – Vertical ground reaction force

UQYBT - Upper quarter y-balance test

YBT - Y balance test

WBLT – Weight bearing lunge test

Introduction

Dynamic postural control is the ability to maintain a stable base while completing a movement (Pollock, Durward, Rowe, & Paul, 2000). This includes movements of the center of mass (COM) within a stationary or moving base of support (BOS). Based on this broad definition a myriad of different tests are used to assess dynamic postural control (Almeida, Monteiro, Marizeiro, Maia, & de Paula Lima, 2017; Glave, Didier, Weatherwax, Browning, & Fiaud, 2016; Gribble, Hertel, & Plisky, 2012; Haitz, Shultz, Hodgins, & Matheson, 2014; Katz-Leurer, Fisher, Neeb, Schwartz, & Carmeli, 2009; Padua et al., 2009; Wikstrom, Tillman, Smith, & Borsa, 2005), which can be grouped into 1) reaching; 2) landing; and 3) hopping tests. These tests require a variable degree of functional mobility, which for the current thesis is defined as the combination of range of motion (ROM) of multiple joints used to accomplish ecological tasks.

The currently available tests of dynamic postural control appear to assess either the lower extremities or the trunk and the upper extremities separately. To the best of my knowledge there are currently no tests that concurrently target joint movements of the trunk, upper and lower extremities and thereby assess the kinetic chain, which is “the combination of several successively arranged joints constituting a complex motor unit” (Steindler, 1977). Multi-directional hand reaches can be developed to impose joint movement demands on the kinetic chain and find application in various overhead sports (i.e. throwing), where different joint movements have been established as important contributors to performance (Roach & Lieberman, 2014). Furthermore, hand reaches can be applied to address proximal influences of the trunk and the lower extremities in patients with shoulder dysfunction (Crosbie, Kilbreath, Hollmann, & York, 2008; Hirashima, Kudo, Watarai, & Ohtsuki, 2007; Kibler & Sciascia, 2016), explore the lumbo-pelvic rhythm in multiple planes of motion in patients with low back pain (LBP) (Laird, Gilbert, Kent, & Keating, 2014; Laird, Kent, & Keating, 2016; Zawadka et al., 2018), and assess lower extremity joint-specific dysfunction (Kivlan, Carcia, Clemente, Phelps, & Martin, 2013). The general aims of this thesis were to develop a new test of dynamic postural control based on multidirectional hand reaches, establish the validity and reliability of the outcome measurements, and to determine the influence of other factors such as anthropometrical measures, level of physical activity, sex and age on outcome measurements.

Background

Postural control

Postural control is a requirement for the maintenance of postures and the execution of purposeful human movement (Pollock et al., 2000), where the postural control system, including the sensory system, central nervous system and musculo-skeletal system, acts to create a stable posture against gravity that serves as a reference for perception and interaction with the external environment (Latash, 2008; Massion, 1994). Postural control is a complex motor skill that covers a myriad of postures and movements and is defined as the ability to maintain, achieve or restore a state of balance during any posture or activity (Pollock et al., 2000; Winter, 1995). Balance – the ability to maintain center of gravity (COG) within the base of support (BOS) (Pollock et al., 2000) – is therefore an operational part of dynamic postural control. Pollock and co-workers refer to the ability to sense when balance is threatened, with the COG moving toward BOS boundaries, and to counteract this with muscular actions as both balance and postural control (Pollock et al., 2000). Furthermore, stability is closely associated with postural control and balance, since stability is based on how much the line of gravity (LOG) can move and the magnitude of external forces that can be counteracted before becoming unbalanced. Thus, better stability is defined as the ability to have a greater displacement of LOG and to counteract greater forces before becoming unbalanced (Pollock et al., 2000). Consequently, postural control, balance and stability are often used as interchangeable terms (Krkeljas, 2018; Pollock et al., 2000). Since postural control is a mechanism of balance regulation that includes stability, postural control will be used throughout this thesis.

The systems framework for postural control described by Horak identifies six resources for effective postural control (Horak, 2006). These are biomechanical constraints, movement strategies, sensory strategies, orientation in space, control of dynamics and cognitive processing. Consequently, testing of postural control is multifactorial and should reflect 1) the ability to configure linked body segments based on their mechanical properties and the internal and external forces acting on these segments to maintain the center of mass (COM) within the BOS; 2) integration of sensory information (visual, proprioceptive, vestibular and cutaneous); and 3) anticipatory and reactive postural adjustments under static, dynamic or perturbed conditions (Massion, 1994; Pollock et al., 2000; Winter, Patla, & Frank, 1990). Such tests are used to assess the presence of impairments, functional limitations and injury risk factors in different populations (Winter et al., 1990). Since postural control is involved in the maintenance of postures and purposeful human movement, tests have to cover a wide range of postures and movements. Thus, a categorization of postural control tests to determine which aspects of postural control are addressed is helpful (Clark, Saxion, Cameron, & Gerber, 2010; Pollock et al., 2000; Winter et al., 1990). The two most common test categories are static and dynamic (Pollock et al., 2000; Winter et al., 1990), with and without perturbations (expected and unexpected). Since the difference between static and dynamic postural control is not clearly established (Krkeljas, 2018) a division of tests into three descriptive categories is helpful: 1) maintain a position with minimal movement (Gribble & Hertel, 2003; Pollock et al., 2000; Winter et al., 1990); 2) maintain a stable base while completing a prescribed movement (movement of COM within a stationary or moving BOS) (Gribble & Hertel, 2003; Hinman, 2000; Pollock et al., 2000; Winter et al., 1990); and 3) reaction to external disturbances/perturbations that are anticipated or not (Pollock et al., 2000; Winter et al., 1990). Based on the magnitude of joint movements that have to be controlled, the first and second categories can be considered static and dynamic postural control tests respectively, to which perturbations (the third category) can be applied. Recently, tests that target dynamic postural control have gained popularity since a higher degree of specificity to functional and athletic tasks can be obtained (Riemann & Caggiano, 1999; Sell, 2012).

Dynamic postural control tests

Dynamic postural control tests that do not require expensive equipment and advanced analysis have a greater chance of clinical application and can therefore be defined as applied tests. Currently there is a myriad of different applied dynamic postural control tests (Almeida et al., 2017; Glave et al., 2016; Gribble et al., 2012; Haitz et al., 2014; Katz-Leurer et al., 2009; Padua et al., 2009; Wikstrom et al., 2005) where the systems framework for postural control (Horak, 2006) can be used to assess the neuromuscular demands addressed by different tests. Specifically, for the purpose of this thesis, the biomechanical constraints (degrees of freedom, strength and limits of stability (LOS)) will be addressed. Degrees of freedom can refer to the number of joints that have to be dynamically controlled. In addition, it could be argued that the magnitude of joint movements to be controlled is also important, since many athletic and functional tasks require larger joint movements. In this thesis, joint mobility demands are used to describe magnitude, the number of joint movements, and their combinations imposed by different tests. The magnitude of joint movements are compared to normative range of motion (ROM) values (Greene & Heckman, 1994). The assessment of strength includes both force regulation (magnitude, rate and duration) and type of contraction (concentric, eccentric, isometric), while LOS are discussed based on the BOS (size, dynamic or static).

Since tests of dynamic postural control include a broad range of movements from different postures (Almeida et al., 2017; Glave et al., 2016; Gribble et al., 2012; Haitz et al., 2014; Katz-Leurer et al., 2009; Padua et al., 2009; Wikstrom et al., 2005) there is no “gold standard” test, but many different tests and outcome measurements with different neuromuscular demands. Based on the similarities of movements tested, the dynamic postural control tests can be grouped as follows: 1) reaching; 2) hopping; and 3) landing (Table 1). In the following sections these test categories are described.

Reaching tests

Reaching tests include the star excursion balance test (SEBT), Y-reach balance test (YBT), seated reach test (SRT), functional reach test (FRT), closed kinetic chain upper extremity stability test (CKCUEST) and upper quarter Y-balance reach test (UQYBT). The primary outcome measurements of these tests are either maximum foot (Gribble et al., 2012) or hand reach in centimetres (cm) (Field-Fote & Ray, 2010; Gorman, Butler, Plisky, & Kiesel, 2012; Radtka, Zayac, Goldberg, Long, & Ixanov, 2017; Thompson & Medley, 2007), except for the CKCUEST, which is a count of reaches in 15 seconds (Tarara, Fogaca, Taylor, & Hegedus, 2016) (Table 1). Greater reach distances or number of reaches are considered to indicate better dynamic postural control.

The foot reaches are the SEBT and the YBT. The SEBT consists of eight maximum foot reaches in different directions at floor height for each foot (Gribble et al., 2012; Hertel, 2008). The YBT, which consists of three foot reaches on each foot, was developed from the SEBT because of the 1) redundancy of measurements of the eight different SEBT reaches (Hertel, Braham, Hale, & Olmsted-Kramer, 2006); 2) sensitivity of specific reaches for identifying patients with chronic ankle instability (Hubbard, Kramer, Denegar, & Hertel, 2007a); 3) differences in muscle activation patterns of the hip (Hubbard, Kramer, Denegar, & Hertel, 2007b); and 4) ability of the anterior, posteromedial and posterolateral reach to predict injury (Plisky, Rauh, Kaminski, & Underwood, 2006; Gribble et al., 2012). Both absolute (cm) and normalized (% leg length) measures are used to quantify reach performance. In addition, the positions of arms, trunk, pelvis and knee relative to the second toe have been used to qualitatively evaluate SEBT and YBT reaches (Ness, Taylor, Haberl, Reuteman, & Borgert, 2015; Piva et al., 2006).

The other four reaching tests are hand reaches measured from different starting positions: standing (FRT), sitting (SRT) and a push-up position (UQYBT and CKCUEST). Specifically, the FRT is a unilateral arm reach (shoulder flexed to 90 degrees, elbow extended and wrist in neutral position) at shoulder height measured in cm (Duncan, Weiner, Chandler, & Studenski, 1990). Other hand reach tests at shoulder height include the lateral (Brauer, Burns, & Galley, 1999) and the multidirectional reach test (forward, lateral and backward hand reaches) (Newton, 2001), which was developed to complement the FRT. A seated variation of the FRT, the SRT, quantifies reaches in the anterior, lateral (Field-Fote & Ray, 2010; Thompson & Medley, 2007), anterolateral and posterolateral direction (Radtka et al., 2017) and is mostly used to assess patients with neurological injuries (Field-Fote & Ray, 2010; Katz-Leurer et al., 2009; Lynch, Leahy, & Barker, 1998). The UQYBT is made up of hand reaches performed from a three-point plank position in the YBT reach directions with the upper extremity tested placed in the center of a testing mat or Y-balance test kit. These arm reaches are commonly normalized to arm length and greater measurements are considered to indicate both better mobility and stability (Gorman, Butler, Plisky, et al., 2012). Additional equipment, such as force plates, has been used to quantify complementary measurements such as COP measures in different hand (Brauer et al., 1999; Duncan et al., 1990; Field-Fote & Ray, 2010) and foot reaches (Bastien et al., 2014b; Pionnier, Decoufour, Barbier, Popineau, & Simoneau-Buessinger, 2016).

All of the aforementioned reach tests are easy to administer and require minimal equipment, such as a yard stick (Duncan et al., 1990), testing mat, tape measure (Gribble et al., 2012) or a Y-balance test kit (Plisky et al., 2009). Different types of reliability (inter-, intra- and test-retest) have been reported for all reaching tests with mostly fair to excellent intraclass correlation coefficients (ICC) based on established criteria (Portney & Watkins, 1993). Furthermore, standard error of measurement (SEM) and coefficient of variation (CV) are fairly consistently reported, while minimal detectable change (MDC) is only reported for the SEBT (Hyong & Kim, 2014; Munro & Herrington, 2010) and the YBT (Freund, Stetts, Oostindie, Shepherd, & Vallabhajosula, 2018; Kenny, Palacios-Derflingher, Owoeye, Whittaker, & Emery, 2018; van Lieshout et al., 2016) (Appendix I).

Overall the neuromuscular demands of these reach tests are rather low. Generally, the force demands are low (i.e. FRT), with the SEBT and the YBT having the greatest force demands. The BOS is different between tests and ranges from small (YBT and SEBT) to large (SRT, UQYBT and CKCUEST). The magnitudes of joint movements elicited by the different tests are mostly low in comparison to established normative ROM values (Greene & Heckman, 1994) except for some ankle joint movements for both the YBT and SEBT (Aminaka & Gribble, 2008; Doherty et al., 2015; Fullam, Caulfield, Coughlan, & Delahunt, 2014; Hoch, Staton, & McKeon, 2011; Kang et al., 2015; Robinson & Gribble, 2008). However, no comparisons can be made for the other reach tests due to the absence of kinematic studies. The SEBT and YBT impose joint mobility demands on the lower extremity, while the FRT, SRT, UQYBT and CKCUEST impose variable demands on the trunk and upper extremities.

Hopping tests

The different hopping tests used to assess dynamic postural control are mostly single or multiple lower extremity hops performed in one or more direction. Specifically, single (single leg hop) or multiple hops in the same or different directions (multiple hops, triple hop, 6-meter timed hop, cross-over hop and the four hops and three contacts) are used. Only one hop test targets upper extremity axial loading: the one-arm hop test (Falsone, Gross, Guskiewicz, & Schneider, 2002) (Table 1). The primary quantitative outcome measurements for most of the hopping tests are either time or distance, with greater distance or shorter time considered to indicate better dynamic postural control. A floor-based photocell system (i.e. Optogait) is used to quantify not only distance but also contact time in the four hops three contacts test (Mani, Brechue, Friesenbichler, & Maffiuletti, 2017). Qualitative assessments have been used more in hopping than in reaching tests. Specifically, a count of balance errors is used in the multiple hop test (Eechaute, Vaes, & Duquet, 2009; Riemann & Caggiano, 1999), while postural orientation error (POE) (Nae, Creaby, Nilsson, Crossley, & Ageberg, 2017), peak knee valgus (Ramirez, Negrete, & Kolber, 2018) and flexion (von Porat, Holmstrom, & Roos, 2008) have been used for the single leg hop test.

Hopping tests are comparable to the reach tests in that they are easy to administer, require minimal equipment, and the reliability (inter-rater and test-retest) of quantitative measurements is good to excellent based on established criteria (Portney & Watkins, 1993) (Appendix II) . Similar to reach tests, SEM is reported in a consistent manner, while CV is only reported for the single leg hop (Augustsson et al., 2006). In contrast, MDC values have been established for four different hop tests (single leg, triple, 6-m timed and cross-over hop tests) (Haitz et al., 2014; Munro & Herrington, 2011; Reid, Birmingham, Stratford, Alcock, & Giffin, 2007) (see Appendix II for details).

The neuromuscular demands for the hopping tests are greater than those for the reaching tests based on force demands and BOS. Both greater magnitude and rate of force are required for better outcomes. In fact, some of the hopping tests are used to assess horizontal lower extremity power (Brughelli, Cronin, Levin, & Chaouachi, 2008). The BOS is small and dynamic for all hopping tests, and it can be argued that jumps in the forward direction have a greater BOS since the LOG can move further to LOS than hops in medial and lateral directions. The joint mobility demands are fairly low and only ankle dorsiflexion approaches normative data (Augustsson et al., 2006). Furthermore, primarily lower extremity joint movements have to be controlled, with the exception of the one-arm hop test (Falsone et al., 2002). Thus, hopping tests mostly target lower extremity dynamic postural control.

Landing tests

Landing is quantified following various bilateral and unilateral jumps in the forward, medial and lateral directions from different heights and horizontal distances (Table 1). Landing tests differ from both reach and hop tests because outcome measurements require advanced equipment (e.g. force plates), processing and analysis of data. This may explain why simpler qualitative assessments such as the POE (Nae et al., 2017) and the landing error scoring system (LESS) (Padua et al., 2009) are more frequently applied to landing than to reach and hop tests (Table 1). However, force plates have become less expensive, with many sports teams and rehabilitation clinics currently using this type of technology. Currently there are three primary outcome measurements in which one or more components of the force data are used: 1) time to stabilization (TTS); 2) dynamic postural stability index (DPSI); and 3) vertical ground reaction force (VGRF). Specifically, the TTS is calculated in three different directions: vertical (TTS V), anterior to posterior (TTS AP), medial to lateral (TTS ML) (Colby, Hintermeister, Torry, & Steadman, 1999; Krkeljas, 2018; Ross, Guskiewicz, & Yu, 2005) and from a resultant vector based on the anterior to posterior and medial to lateral force signals (Ross, Guskiewicz, Gross, & Yu, 2008). Two different methods to calculate the TTS measurements are currently used (Colby et al., 1999; Krkeljas, 2018; Ross et al., 2008; Ross et al., 2005) to quantify the time taken for a force signal to return to within the range of normal variation based on a static reference trial. A shorter time is considered to indicate better dynamic postural control. In contrast, DPSI quantifies variations in the force signal for a given time frame in the vertical, medial to lateral, and anterior to posterior directions, and for the overall signal (Wikstrom, Arrigenna, Tillman, & Borsa, 2006; Wikstrom et al., 2005). Smaller values represent better dynamic postural control (Table 1). The force signal, in terms of the vertical ground reaction force (VGRF), is also analysed in a simpler manner than for the TTS and DPSI measurements, since the magnitude of absolute and normalized VGRF (Read, Oliver, Croix, Myer, & Lloyd, 2016; Troester, Jasmin, & Duffield, 2018), time to VGRF (Read et al., 2016), and impulse (Troester et al., 2018) are used as outcome measurements. Smaller values are considered to represent better dynamic postural control (Table 1). Since TTS and DSPI measurements are based on variations in force signals over time they contain more information (continuous measurement) about dynamic postural control than the different discrete PVGRF measurements.

The most consistently used outcome measurements appear to be the TTS and VGRF. Test-retest reliability is most frequently reported and ranges from poor to excellent (Appendix III). Of the different outcome measurements, the DPSI appears to have the best test-retest reliability (good to excellent), with one notable exception (poor) for the medio-lateral direction in the forward jump landing (Wikstrom et al., 2005). In addition, better reliability of the DPSI measurements compared to the TTS measurements were observed when calculated from the same data (Wikstrom et al., 2005). However, the DPSI has only been used for two different landing tasks, with three studies reporting on reliability (Sell, 2012; Wikstrom, Tillman, Kline, & Borsa, 2006; Wikstrom et al., 2005). Overall, the reliability of landing tests appears to be not as good as the reliability of the reach and hop tests.

The neuromuscular demands associated with landing tasks are comparable to those of the hopping tests. However, the eccentric force requirement dominates. The magnitudes of the joint movements associated with these tests are low in comparison to normative data (Greene & Heckman, 1994) and limited to lower extremity joint movements. Similar to the hopping tests, the BOS is dynamic with jump direction-specific demands.

Neuromuscular demands of current dynamic postural control tests

The dynamic postural control tests summarized in Table 1 have different neuromuscular demands. Specifically, greater force demands are imposed in hopping and landing tests in comparison to reaching tests (i.e. SEBT). Furthermore, the landing tests primarily have eccentric force demands, while hopping tests have both concentric and eccentric modes of muscular activation. Test-specific BOS characteristics of the different tests such as size (small vs. large), and whether the tests are static (standing in one place) or dynamic (changing from one place to another) influence stability and thereby the ability to control posture. In addition, the different dynamic postural control tests require control of different movements, but the magnitudes of these joint movements are rarely presented, except for the SEBT, YBT (Aminaka & Gribble, 2008; Doherty et al., 2015; Fullam et al., 2014; Hoch et al., 2011; Kang et al., 2015; Robinson & Gribble, 2008) and for some hopping tests (Augustsson et al., 2006). The reported mobility demands of these tests when compared to normative ROM data (Greene & Heckman, 1994) are mostly low. Furthermore, it appears that no single test imposes simultaneous mobility demands on the trunk, lower and upper extremity joints; tests tend to focus on the lower extremities (i.e. SEBT, YBT, hopping and landing tests) or trunk and upper extremities alone (i.e. UQYBT). Thus, tests that simultaneously impose joint mobility demands on the trunk and the upper and lower extremities should be further explored.

Mobility

How much a joint or series of joints can move in a given plane and direction is defined as joint flexibility (Gleim & McHugh, 1997; S. Hall, 2007; McGinnis, 2005; Watkins, 2010), while joint mobility is defined as the ease of movement through a range of motion (ROM) (McGinnis, 2005). The American Physical Therapy Association defines joint mobility as the capacity of a joint to move passively, taking into account the joint surfaces and surrounding tissues (American Physical Therapy, 2001). Based on these definitions it is difficult to differentiate between joint flexibility and mobility, which has led to these terms being used somewhat interchangeably. Joint mobility or flexibility measurements are traditionally obtained using goniometry (Greene & Heckman, 1994; Moore, 1949) and normative data have been established (Greene & Heckman, 1994). However, such goniometric measurements have some inherent shortcomings since only information about uniplanar and unidirectional movements of specific joints is obtained, without information about their role in the kinetic chain. Furthermore, the neuromuscular control demands are low since one isolated joint movement is performed either actively or passively. Based on the principle of specificity, such measurements have limited transfer to athletic and functional tasks, which require combinations of joint movements of variable magnitudes depending on the requirements of the task to be executed. Tests of functional mobility, defined as the combination of the ROM of multiple joints used to accomplish activities of daily living and athletic performance, can address these shortcomings. Such functional mobility tests require dynamic postural control, but their main purpose is to impose joint mobility demands, and specifically target the magnitude of joint movements.

Functional mobility tests

Based on the definition described previously, and to ensure construct validity, a functional mobility test should: 1) elicit a combination of different joint movements that contribute to the measurement; 2) be specific or similar to ecological movements; and 3) quantify the magnitude and/or the quality of movement. However, functional mobility is also used to describe activities of daily living and living independence. Thus, functional mobility tests that target factors such as walking (e.g. Timed Up and Go test, 10-meter walk test, 6-minute walk test) and functional independence (e.g. Functional independence measure and community balance and mobility scale) do not fulfil the previously described criteria and will not be discussed. However, the following tests do fulfil the criteria: 1) SEBT and YBT; 2) UQYBT; 3) functional movement screen (FMS); 4) selective functional movement assessment (SFMA); and 5) weight bearing lunge test (WBLT) (Table 1).

Star excursion and Y-balance reach test

The SEBT and YBT are considered tests of dynamic postural control, as described previously; however, they can also be regarded as tests of functional mobility. Kinematic analyses of different SEBT reaches have established that three-dimensional trunk and lower extremity joint movements of variable magnitudes are used to assume the different maximum reach positions (Aminaka & Gribble, 2008; Doherty et al., 2015; Fullam et al., 2014; Hoch et al., 2011; Kang et al., 2015; Robinson & Gribble, 2008). When the elicited joint movements are compared to normative ROM data (Greene & Heckman, 1994) only ankle dorsiflexion and eversion approach normative ROM values. In fact, ankle dorsiflexion is correlated with normalized (Basnett et al., 2013), but not absolute SEBT reach measurements (Gribble & Hertel, 2003). Furthermore, increased foot mobility has been reported to increase normalized reach measurements (Wassinger, Rockett, Pitman, Murphy, & Peters, 2014).

Upper Quarter Y-balance reach test

The UQYBT described previously was developed to target both upper extremity and trunk stability and mobility. Gorman and co-authors claim that the different reaches maximally challenge both mobility and stability (Gorman, Butler, Plisky, et al., 2012). However, this statement has not been substantiated through studies that have explored COM, COP or kinematic measurements.

Functional movement screen (FMS)

Based on the aforementioned criteria, both the deep squat and the in-line lunge of the FMS can be considered tests of functional mobility. These are two of seven tests that are subjectively graded and make up the FMS (Cook, Burton, & Hoogenboom, 2006a, 2006b). Lower extremity kinematic analysis of participants able to complete the squat without compensation (FMS score: 3) showed they used greater ankle dorsiflexion, knee and hip flexion in the deep squat position than those who were unable to complete the movement (FMS score: 1) (Butler, Plisky, Southers, Scoma, & Kiesel, 2010). Furthermore, the maximum excursions of these joint movements during the squat for the participants graded as normal (FMS score: 3) were comparable to normative ROM values (Butler et al., 2010; Greene & Heckman, 1994). Reliability of the overall FMS score is good (Bonazza, Smuin, Onks, Silvis, & Dhawan, 2017; Cuchna, Hoch, & Hoch, 2016), while the squat test by itself has moderate to conflicting and moderate evidence of inter-rater and intra-rater reliability, respectively (Moran, Schneiders, Major, & Sullivan, 2016) (Appendix IV).

The deep squat is also a part of the selective functional movement assessment (SFMA), which is a category and criterion-based qualitative test battery to assess movement dysfunction in patients with known musculoskeletal dysfunctions (Glaws, Juneau, Becker, Di Stasi, & Hewett, 2014). Moderate to good and poor to good categorical intra-rater and inter-rater reliability have been reported, respectively (Glaws et al., 2014). As for the criterion-based overall score, poor to good and poor intra-rater and inter-rater reliability have been reported (Glaws et al., 2014) (Appendix IV). In addition, other scoring systems have been used for the deep squat. Specifically, the squat movement competency scale has good to excellent reliability (Edwards & Liberatore, 2018). However, neither the SFMA grading systems nor the squat movement competency scale have been compared to lower extremity joint kinematics. Thus, it appears that the criterion-based grading of the deep overhead squat is the best assessment strategy.

Joint kinematic measurements of the in-line lunge have not yet been reported. Consequently, joint movement requirements of the in-line lunge cannot be established, and comparisons to normative ROM data are not possible. Since kinematic analyses of forward lunges have been reported, such data can be used as a general representation of the joint movements required to perform the in-line lunge. However, a forward lunge differs from an in-line lunge in that it is not performed on a line and the step length is usually longer (Cook et al., 2006a). The forward lunge elicits less ankle dorsiflexion, knee and hip flexion (Farrokhi et al., 2008; Riemann, Congleton, Ward, & Davies, 2013; Riemann, Lapinski, Smith, & Davies, 2012) than the squat (Butler et al., 2010), where shorter step-lengths result in increased ankle dorsiflexion and decreased hip flexion, while knee flexion remains relatively unchanged (Riemann et al., 2013). As previously described, the overall reliability of the FMS is good (Bonazza et al., 2017; Cuchna et al., 2016), while the in-line lunge test has conflicting and moderate evidence for inter-rater and intra-rater reliability, respectively (Moran et al., 2016) (Appendix IV). Overall, it appears that the squat assessed by the FMS scoring system is a better test of functional mobility test than the in-line lunge test.

Selective functional movement assessment (SFMA)

In addition to the squat described previously, the SFMA also consists of multi-segmental flexion, extension and rotation tests (Glaws et al., 2014), which can be considered functional mobility tests. However, neither criterion nor category assessment of these tests have been compared to kinematic data. This is surprising considering that the purpose of the different tests is to identify movement dysfunction based on observation of the execution of the tests. Kinematic analysis of movements similar to these tests have been reported and show that multiple joints and segments contribute to the maximum reach position (Alqhtani, Jones, Theobald, & Williams, 2015; Esola, McClure, Fitzgerald, & Siegler, 1996; Leardini, Biagi, Merlo, Belvedere, & Benedetti, 2011; Lee & Wong, 2002; Song, Jo, Sung, & Kim, 2012; Sung, 2014; Sung, Yoon, & Lee, 2010; Tafazzol, Arjmand, Shirazi-Adl, & Parnianpour, 2014). However, these studies report trunk and/or hip movements without any quantitative or qualitative outcome measurement in flexion (Alqhtani et al., 2015; Esola et al., 1996; Tafazzol et al., 2014), extension (Leardini et al., 2011; Lee & Wong, 2002), axial rotation (Leardini et al., 2011; Lee & Wong, 2002; Song et al., 2012; Sung, 2014; Sung et al., 2010) and lateral flexion tests (Laird et al., 2016; Tojima, Ogata, Inokuchi, & Haga, 2016). The trunk movements elicited by these tests are comparable to established normative values (Greene & Heckman, 1994). The categorical inter- and intra-rater reliability of the SFMA tests ranges from poor to excellent. Furthermore, the criterion inter- and intra-rater reliability have been reported to be poor and poor to good respectively (Glaws et al., 2014) (Appendix IV). Based on the lack of reliability and the lack of kinematic analysis with comparisons to the categorical and criterion-based scoring systems, these tests appear not to be good tests of functional mobility.

Weight bearing lunge test (WBLT)

Dorsiflexion mobility is primarily targeted by the WBLT (Bennell et al., 1998). Since the support foot is allowed to be in contact with ground, the BOS is large, which increases stability and thereby might favour joint mobility in comparison to the SEBT. Outcome measurements (degrees and cm) have been found to be highly correlated with kinematic data (Hall & Docherty, 2017). In addition, dorsiflexion ROM values obtained from the test correspond to normative reference values (Greene & Heckman, 1994; Powden, Hoch, & Hoch, 2015). The test has been reported to have good to excellent intra- and inter-rater reliability (Powden et al., 2015) (Appendix IV). The WBLT appears to be a good test of functional mobility, especially since the torque applied to the ankle in standing is much greater than what can be applied using traditional methods (Bennell et al., 1998).

Neuromuscular demands of current functional mobility tests

The functional mobility tests summarized in Table 1 have a static BOS that varies in size from large (UQYBT) to small (SEBT and YBT). Furthermore, the force demands are different since a unilateral squat has a greater force demand than a bilateral squat, which in turn has greater force demands than the SFMA multi-segmental mobility tests. Similar to the dynamic postural control tests there is no single test that imposes joint mobility demands on the trunk, lower and upper extremity joint movements simultaneously. Specifically, lower extremity joint mobility demands are imposed by the overhead deep squat, in-line lunge, SEBT, YBT and WBLT, while the SFMA and UQYBT target the trunk and upper extremities.

Table 1. *Tests of dynamic postural control and functional mobility*

Category	Test	Description	Equipment	Measurement(s)
Reaching tests	Star excursion balance test (SEBT)	Eight maximum horizontal foot reaches (floor height) at 45-degree intervals on each foot (Gribble et al., 2012).	Optional testing mat that identifies reach directions with marks at 2-cm intervals.	**Quantitative** Maximum reach (cm) commonly normalized to leg length (%) or composite score (sum of reaches). Higher scores indicate better performance (Gribble et al., 2012). **Qualitative** Criterion-based rating of movement and position of arms, trunk, pelvis and knee relative to 2nd toe and loss of balance (Ness et al., 2015; Piva et al., 2006).
	Y-balance reach test (YBT)	Three maximum horizontal foot reaches (anterior (A), posteromedial (PM) and posterolateral (PL)) on each foot (Hertel, 2008). Subset of the SEBT.	Optional testing mat that identifies reach directions and marks at 2-cm intervals or Y-balance test kit (Plisky et al., 2009).	**Quantitative** Same as SEBT **Qualitative** Same as SEBT
	Seated reach test (SRT)	Maximum horizontal hand reaches in the anterior, lateral (Field-Fote & Ray, 2010; Thompson & Medley, 2007), anterolateral and posterolateral direction (Radtka et al., 2017) from a seated position without loss of balance.	Tape measure or stick with centimeter measure.	**Quantitative** Maximum reach (cm) (Field-Fote & Ray, 2010; Radtka et al., 2017; Thompson & Medley, 2007).
	Functional reach test (FR)	Maximum unilateral horizontal hand reaches from a bilateral standing position in the anterior (Duncan et al., 1990), lateral (Brauer et al., 1999) and a posterior overhead direction (Newton, 2001).	Sliding track, tape measure on wall, yard stick (Duncan et al., 1990; Newton, 2001), measurement grid (Brauer et al., 1999)	**Quantitative** Reach distance (cm) (Newton, 2001) and COP excursion (Brauer et al., 1999; Duncan et al., 1990)
	Closed kinetic chain upper extremity stability test (CKCUEST)	From a push-up position with hands 36 inches apart alternately touch with one hand on the opposite hand (Goldbeck & Davies, 2000).	Tape measure with marks on the floor/ground and stop watch.	**Quantitative** Number of touches in 15 seconds (Goldbeck & Davies, 2000; Tarara et al., 2016)
	Upper quarter Y-balance reach test (UQYBT)	Maximum hand reaches from a push-up position in the same directions as the YBT (Gorman, Butler, Plisky, et al., 2012).	Y-balance test kit or optional testing mat that identifies reach directions with marks at 2-cm intervals.	**Quantitative** Maximum reaches (cm) normalized to arm length or composite score (sum of reaches) (Gorman, Butler, Plisky, et al., 2012).
Hopping tests	Multiple hop	10 single leg hops with hands on hips to 11 2x2 cm tape targets (Eechaute, Vaes, & Duquet, 2008; Eechaute et al., 2009; Riemann & Caggiano, 1999) organized as follows: diagonal dimension 45% of height (Eechaute et al., 2008; Riemann & Caggiano, 1999) and adjacent distance 32% of height (Eechaute et al., 2008).	Tape to identify targets. Video camera for qualitative assessment. Digital chronometer for time (Eechaute et al., 2008).	**Quantitative** Time (s) (Eechaute et al., 2008). **Qualitative** Balance errors counted for 30 hops on each foot (Eechaute et al., 2009) or count of balance and landing errors (Riemann & Caggiano, 1999).

	Test	Description	Equipment	Measurement(s)
	Single leg hop	One maximum single leg hop for distance and maintain landing for minimum of 2 seconds (Ramirez et al., 2018).	Standard tape measure and video camera for qualitative assessment. Specific software for video analysis can be used.	**Quantitative** Distance (m), percentage of leg length (LL%) (Barber, Noyes, Mangine, McCloskey, & Hartman, 1990) or limb symmetry index (LSI) > 85% is normal (Barber et al., 1990; Reid et al., 2007). **Qualitative** Peak knee valgus angle (°) during landing (Ramirez et al., 2018). Knee flexion in landing (11-point scale) (von Porat et al., 2008).
	Triple hop	Three consecutive maximum hops on each leg (Bolgla & Keskula, 1997).	Standard tape measure (cm) and LSI (Reid et al., 2007)	**Quantitative** Distance (m) and percentage of leg length (LL%).
	6-m timed hop	Time to hop an established 6-m distance (Bolgla & Keskula, 1997).	Standard tape measure (cm), digital chronometer (Eechaute et al., 2008), standard stop watch (Bolgla & Keskula, 1997), electronic timing gates (Munro & Herrington, 2011).	**Quantitative** Time (s) and LSI (Reid et al., 2007).
	Cross over hop	Three maximum forward consecutive hops on each leg that cross a center line (Bolgla & Keskula, 1997).	Standard tape measure (cm), stop watch and electronic timer (s) and LSI (Reid et al., 2007).	**Quantitative** Distance (m), time (s) or LSI (Reid et al., 2007).
	Four hops, three contacts (4H3C)	Four maximum forward consecutive hops on one leg (Mani et al., 2017).	Standard tape measure (cm), stop watch (s) or floor based photocell system (i.e. Optogait) (Mani et al., 2017).	**Quantitative** Hop distances (m) and contact time (s) (Mani et al., 2017).
	One-arm hop test	Five hops off one upper extremity from a push-up position onto to a non-slippery 10.2 cm step as quickly as possible (Falsone et al., 2002).	Standard stop watch.	**Quantitative** Time (s) (Falsone et al., 2002).
Landing tests	Forward jump landing (FJL)	Bilateral stance at 40% of height, 70 cm, 1m or 125% of leg length (Krkeljas, 2018; Meardon, Klusendorf, & Kernozek, 2016; Ross et al., 2005; Sell, 2012; Troester et al., 2018) from the center of a force plate. Bilateral jump to 50-55% or maximum jump height (Krkeljas, 2018; Meardon et al., 2016; Ross et al., 2005; Troester et al., 2018; Wikstrom et al., 2005) or over 12-inch hurdle (Sell, 2012) with unilateral leg landing (stick and hold for 3 to 20 seconds) on a force plate with arms on hips (Krkeljas, 2018; Ross et al., 2005; Wikstrom et al., 2005). Position of contralateral limb hip flexion~30° and knee flexion~30° (Meardon et al., 2016).	Force plate	**Quantitative** **Kinetic time-to-stabilisation (TTS):** Method 1: Time from vertical (V) ground reaction force (GRF) > 10N to when VGRF stays within 5% of body weight (BW), or when medio-lateral (ML), anterior-posterior (AP) or resultant vector (RV) of GRF approaches zero and stays within 5% of average variation (Colby et al., 1999; Krkeljas, 2018) or 0.25 SD of the series mean (Wikstrom et al., 2005). Method 2: Time to when an unbounded third order polynomial of the force signal intercepts the reference value based on the range of variation of force signal (AP,ML,RV) ±3standard deviation normalized to body weight (Ross et al., 2008; Ross et al., 2005). **Dynamic postural stability index (DPSI):** Unitless measurement. Onset defined as vertical GRF> 10N. Mean square deviations around a 0 point. Deviations are calculated along the frontal (MLSI), sagittal (APSI) and vertical (VSI) (body weight -z) axes of the force plate divided by number of data points. The DPSI is the composite of these three components and outcome

	Test	Description	Equipment	
	Forward hop	Unilateral stance with hands on hips at 75% of maximum hop distance or one leg length away from center of the force plate. Hands on hips during hop and landing (stick and hold for at least 5 seconds) (Colby et al., 1999; Read et al., 2016).	Force plate	measurements are obtained for 3, 5 or 10 seconds (Wikstrom, Arrigenna, et al., 2006; Wikstrom et al., 2005) with 3 seconds being recommend (Wikstrom et al., 2005). **PVGRF** Peak vertical ground reaction force (PVGRF) (Read et al., 2016). **rPVGRF** Peak vertical ground reaction force (PVGRF) normalized to body mass (Troester et al., 2018). **Take-off rPVGRF** Peak vertical ground reaction force (PVGRF) normalized to body weight during take-off phase (specific to the drop-jump test) (Mohammadi et al., 2012). **Time to PVGRF** Time from initial contact (>10N) to PVGRF (Read et al., 2016). **Loading rate** Peak vertical ground reaction force (PVGRF) divided by time (N/s) (Mohammadi et al., 2012). **rIMP** Landing impulse (IMP) normalized to body mass (Troester et al., 2018). **Kinematic TTS:** Reference is mean posture (bilateral stance) and standard deviation (SD). Mean and SD from a moving window (2 seconds) during landing are compared to the reference value and when within mean±1SD of reference value and remains so for subsequent time intervals the midpoint of the first time interval is used as kinematic TTS (de Noronha, Refshauge, Crosbie, & Kilbreath, 2008). **COM-COP** Maximum relative displacement between center of mass (COM) and center of pressure (COP) calculated at 2000 milliseconds after contact (Huang, Chen, Lin, & Lee, 2014). **Qualitative** **Postural Orientation Error (POE)** Seven segment specific rating on a four point ordinal scale (0-3) with 0 as good and 3 as very poor of 1) arm, 2) trunk, 3) hip joint, 4) medial knee-to-foot position (MKFP), 5) foot pronation, 6) kinematic asymmetry and 7) joint flexion on landing (Nae et al., 2017). **Landing Error Scoring System (LESS)** 17-item scoring of landing technique errors of the lower extremities and trunk during the different phases of the drop-jump (Padua et al., 2009).
	Lateral jump landing	Bilateral stance 33% of body height away from the force plate. Bilateral jump laterally over a 6-inch hurdle with unilateral landing (stick and hold for 10 seconds) with hands on hips (Sell, 2012). Position of contralateral limb hip flexion~30° and knee flexion~30°(Meardon et al., 2016).	Force plate	
	Diagonal forward jump landing	Bilateral stance at 1.5 times leg length from center of force plate. Bilateral diagonal (45°) forward jump with unilateral landing (stick and hold for 20 seconds) with hands on hips. No set requirement for jump height (Steib, Zech, Hentschke, & Pfeifer, 2013).	Force plate	
	Forward drop landing (FDL)	From a 19 to 40-cm-high platform drop off forward with unilateral landing (stick and hold for 10 seconds) in the center of a force platform with hands on hips (Colby et al., 1999; Krkeljas, 2018).	Force plate	
	Lateral drop landing (LDL)	From a 16 to 40-cm-high platform drop off laterally with unilateral landing (stick and hold for 5 to 10 seconds) in the center of a force platform with hands on hips (Huang et al., 2014; Krkeljas, 2018).	Force plate	
	Medial drop landing	From a 16-cm-high platform drop off medially with unilateral landing (stick and hold for 5 seconds) in the center of a force platform with hands on hips (Huang et al., 2014).	Force plate	
	Drop and stick	From a 50-cm drop off anterior with bilateral landing (stick landing with time interval not defined) in the center of a force platform. (Tran et al., 2015).	Force plate	

	Test	Description	Equipment	
	Drop-jump	Drop off a 30 to 40-cm platform (Hewett et al., 2005; Mohammadi et al., 2012) with an immediate maximum bilateral (Hewett et al., 2005) or unilateral jump (take-off phase) (Mohammadi et al., 2012) with a subsequent unilateral landing. Arms used freely for balance purposes (Hewett et al., 2005; Mohammadi et al., 2012)	Force plate	
	Single leg counter movement jump	Unilateral stance, hands on hips, opposite hip flexed to 90° jump as high as possible from a self-selected depth. Stick landing and hold for five seconds (Read et al., 2016).	Force plate	
Functional mobility	Squat movement competency screen (SMCS)	Squat movement performed without a load and arms at the side with a one second pause in the bottom position (Edwards & Liberatore, 2018).	Video camera	**Qualitative** Movement competency scale. Analysis of film from a frontal and sagittal view based on an overall impression of the movement and not based on segmental movement criteria. A 0 to 10-point scale with 10 being the best score (Edwards & Liberatore, 2018).
	Functional movement screen (FMS)	FMS consists of seven fundamental movement patterns with two movement patterns fulfilling the functional mobility inclusion criteria: 1) deep squat (DS) and 2) the in-line lunge (ILL) (Cook et al., 2006a).	Assessment forms. Both the DS and the ILL requires a stick while the ILL is commonly done on a foot-wide, 2 cm high and about 1.5 m long measuring device with knee of the back leg placed directly behind the forward lunging foot (Cook et al., 2006a). Video camera for quantitative assessment of joint movements.	**Qualitative** Test specific criteria for each score has been defined and graded (0-3) (Cook et al., 2006a). **Quantitative** Sagittal view of deep squat with video camera for joint movement analysis (i.e. Coaches Eye) and motion capture (i.e. Vicon).
	Selective functional movement assessment (SFMA)	SFMA consists of ten different movement patterns where the following tests fulfil functional mobility inclusion criteria: 1) multi-segmental flexion, 2) multi-segmental extension, 3) multi-segmental rotation, 4) overhead deep squat (Glaws et al., 2014).	Assessment forms	**Categorical** Each test categorized as follows: 1) functional non-painful, 2) functional-painful, 3) dysfunctional-non-painful and 4) dysfunctional painful (Glaws et al., 2014). **Criterion** 34-point criterion checklist that identifies if criteria are met (Glaws et al., 2014).
	Weight bearing lunge test (WBLT)	Maximum knee reach toward a target in a lunged position while maintaining heel in contact with the ground (Bennell et al., 1998).	Goniometer (Bennell et al., 1998; Worsley, Conington, Stuart, Patterson, & Bader, 2018), inclinometer (Worsley et al., 2018), Dorsiflex iPhone app (Balsalobre-Fernandez, Romero-Franco, & Jimenez-Reyes, 2018) or an F-Flex device (Worsley et al., 2018).	**Quantitative** Dorsiflexion: degrees (°) Distance to wall or other target: centimeters (cm)

The dynamic postural control continuum

The 27 dynamic postural control and functional mobility tests described in Table 1 are organized in Figure 1 based on BOS and force demands. Specifically, the BOS can be described based on size (small vs. large), and whether it is static (standing in one place) or dynamic (changing from one place to another), while force demands can be described from low to high. Such an organization creates a continuum based on the biomechanical constraints associated with dynamic postural control. Also, such an organization highlights the absence of a “gold standard”, since there is little overlap between tests. However, it is important to note that this represents one way to present a continuum of dynamic postural control. In fact, similar continuums have previously been described based on balance (Glave et al., 2016) and sensorimotor measures (Hertel, 2008). Specifically, the continuum was defined as follows: the horizontal BOS axis was divided into two major categories, static and dynamic (grey), which ranged from small to large. The vertical axis represents force demands from low to high (Figure 1). Reaching tasks and functional mobility tests have static BOSs of different sizes with increasing force demands (i.e. deep overhead squat to SEBT). Landing and hopping tests have dynamic BOSs with landing tests considered to have lower force demands since eccentric muscle action is primarily targeted in one single action, whereas hopping tests have mostly repetitive concentric and eccentric force demands. Both hopping and landing tasks were differentiated based on their direction, with the BOS considered smaller for medial to lateral movements than for anterior to posterior movements. It can be hypothesized that there are lower dynamic postural control demands in tests with lower force demands and supported by a large static BOS, than in tests with higher force demands and a small BOS. A diagonal line (ascending left to right) was placed in Figure 1 to visualize this hypothetical relationship.

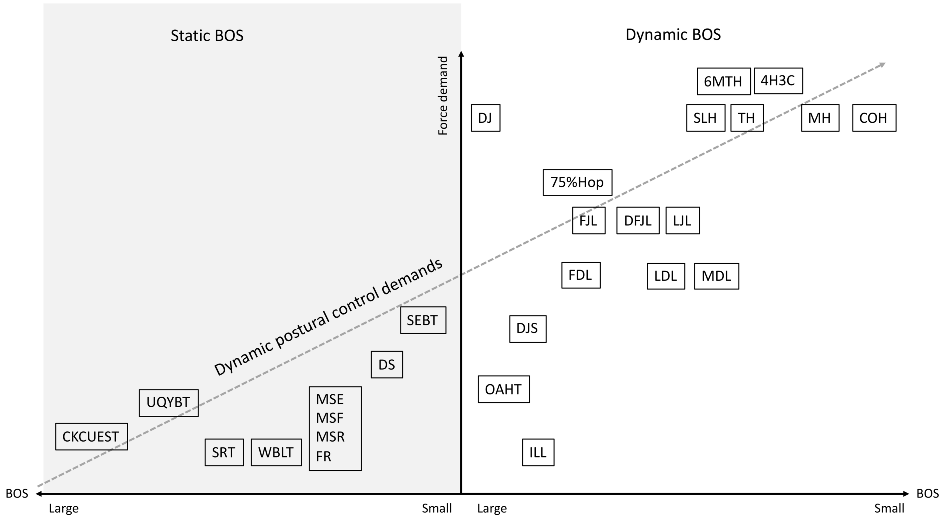

Figure 1. Continuum of dynamic postural control tests. *The vertical axis represents force demand from low to high and the horizontal axis represents the size of the BOS. The vertical axis divides the horizontal axis into two categories of static (grey) and dynamic BOS (white). These two categories are divided into subcategories of large and small BOS. Based on these criteria all tests identified in the thesis of dynamic postural control and functional mobility were identified. The diagonal line ascending from left to right represents demand for dynamic postural control. Abbreviations: BOS = Base of support; CKCUEST = Closed kinetic chain upper extremity stability test; UQYBT = Upper quarter Y-balance test; SRT = Seated reach test; WBLT = Weight bearing lunge test; DS = Deep squat; MSE = Multi-segmental extension; MSF = Multi-segmental flexion; MSR = Multi-segmental rotation; SEBT = Star excursion balance test; OAHT = One arm hop test; DJS = Drop jump and stick; DJ = Drop jump; FJL = Forward jump landing; 75%Hop = Forward hop at 75% of maximum distance; LJL= Lateral jump landing; DFJL = Diagonal forward jump landing; FDL = Forward drop landing; LDL = Lateral drop landing; MDL = Medial drop landing; MH = Multiple hop; SLH = Single leg hop; TH = Triple hop; 6MTH = 6-m timed hop; COH = Cross over hop; 4H3C = Four hops, three contacts*

Shortcomings of current tests

The continuum of dynamic postural control tests allows for a comparison between tests and identification of the shortcomings of current tests. The joint mobility demands imposed on the kinetic chain, described as “the combination of several successively arranged joints constituting a complex motor unit” (Steindler, 1977) are variable. It is apparent that the tests on the static half of the continuum – WBLT, SEBT and the deep overhead squat – impose joint mobility demands primarily on the lower extremities, with the exception of the shoulder joints in the deep overhead squat. The multi-segmental tests (flexion, extension, lateral flexion and rotation), as well as the UQYBT, predominantly impose joint mobility demands on the trunk and the upper extremities, while both the SRT and FR have low joint mobility demands. Overall, tests on the static half of the continuum impose greater demands on the magnitude of joint movements. The exceptions are hopping tests, where ankle dorsiflexion approaches normative data (Augustsson et al., 2006).

Further analyses of the continuum show that most of the tests have largely unidimensional joint mobility demands in the sagittal (squat, WBLT, in-line lunge, multi-segmental flexion, hop and landing tests), frontal (SEBT: medial and lateral reach) or transverse plane (multi-segmental rotation). One notable exception is the multiplanar SEBT (Doherty et al., 2015; Kang et al., 2015; Robinson & Gribble, 2008). Thus, no test or test batteries of dynamic postural control that impose uni- or multi-dimensional joint mobility demands on the kinetic chain are currently available. In fact, such kinetic chain tests have been advocated (Kibler, Press, & Sciascia, 2006; Kibler & Sciascia, 2016), which might allow for a better understanding of how different joints and regions interact and influence each other (Wainner, Whitman, Cleland, & Flynn, 2007).

Hand reaches can be used to impose joint mobility demands on the kinetic chain. One hand reach test would not be sufficient to target the many degrees of freedom of the ankle, knee, hip, trunk and shoulder joints. Therefore, multiple hand reach tests have to be developed. In order to impose demands on both magnitude and different joint movement combinations, hand(s) reaching at different vertical targets (i.e. overhead, shoulder and floor height) have to be used.

Test development

As a part of any test development it is important that the fundamental test properties of validity and reliability are considered.

Content validity

Three practitioners – Ola Eriksrud, Jessica Parnevik-Muth and Ali Ghelem – made up the group of experts that developed the HSEBT. Their clinical and practical experience ranged from 15 to 22 years, and all group members contributed equally to the development. The objective of the group was to develop a test of dynamic postural control and functional mobility that would impose joint mobility demands on the kinetic chain reflective of the theoretical basis (i.e. definitions of dynamic postural control and functional mobility). Content (or logical validity) then evolved from the planning and creation of the test.

Joint movements

The kinetic chain joint movements (degrees of freedom) to be targeted by the test were three-dimensional joint movements of the ankle-foot complex, knee, hip, trunk and shoulder joints. Specifically, the trunk was defined as the thoracic and lumbar spine, while the shoulder joint represented both the glenohumeral joint and scapulothoracic articulation, which is known to have a close and highly coordinated interaction (Crosbie et al., 2008). Furthermore, the interaction of multiple joints of the foot complex (Lundberg, Goldie, Kalin, & Selvik, 1989; Lundberg, Svensson, Bylund, Goldie, & Selvik, 1989) was regarded as one segment and defined as the ankle joint. The other upper extremity joints; the elbow, forearm, wrists and fingers, as well as the cervical spine, were not targeted by the test. A summary of joint movements targeted by the test is presented in Table 2.

Task and reach directions

In order to impose joint mobility demands on the aforementioned joint movements, hand reaches from standing were chosen. Current standing reach tests, as described previously, have low mobility demands (Brauer et al., 1999; Duncan et al., 1990). However, the backward reach introduced by Newton (Newton, 2001) imposes hip and trunk extension joint mobility demands, while hand reaches to ground level do the same for lower extremity and trunk flexion joint movements (Kivlan et al., 2013). Both overhead reaches and reaches to the ground can be considered ecological movements, which elicit coordinated joint movement contributions (Stapley, Pozzo, Cheron, & Grishin, 1999). Considering that hand reaches in different directions describe different LOS (Newton, 2001) and that one purpose was to impose mobility demands on the joint movements identified in Table 2, multiple reaches beyond merely forward and backward reaches were developed. For this purpose, the SEBT reach directions served as a reference (Gribble et al., 2012). However, the SEBT reach directions (based on the stance foot) can be confusing when the stance foot is changed. Therefore, hand reaches were defined from the anatomical position where the anterior (A0) and posterior (P180) reaches divide the body into right (R) and left (L) halves. Each half was then divided into 45-degree increments to define the additional six hand reaches: R45, R90, R135, L135, L90 and L45. Collectively these reaches are defined as horizontal reaches. The horizontal reaches are divided into anterior reaches (L45, A0 and R45) and defined as flexion movement patterns, while posterior reaches (R135, P180 and L135) are defined as extension movement patterns. In order to specifically target transverse plane joint mobility demands both a left (LROT) and a right rotational reach (RROT) were developed. Since the test is mostly based on hand reaches in the same directions as the SEBT, the name hand reach star excursion test (HSEBT) was chosen.

Equipment

To facilitate measurements, a testing mat was designed identifying the reach directions with marks using the metric system (Figure 2). Specifically, the testing mat consisted of eight reach directions extending from a common center point at 45-degree intervals and marked at 1 cm intervals, which defined the resolution of the measurement. Furthermore, at each 10 cm radius (up to 90 cm) a concentric circle was added. These circles were marked with 10 degree intervals in order to measure rotational reaches, measured in degrees. Having defined the task (hand reaches), a general starting position (standing) and reach directions, specific testing procedures were developed for each reach as follows: 1) starting position, 2) movement, 3) measurement and 4) ending position.

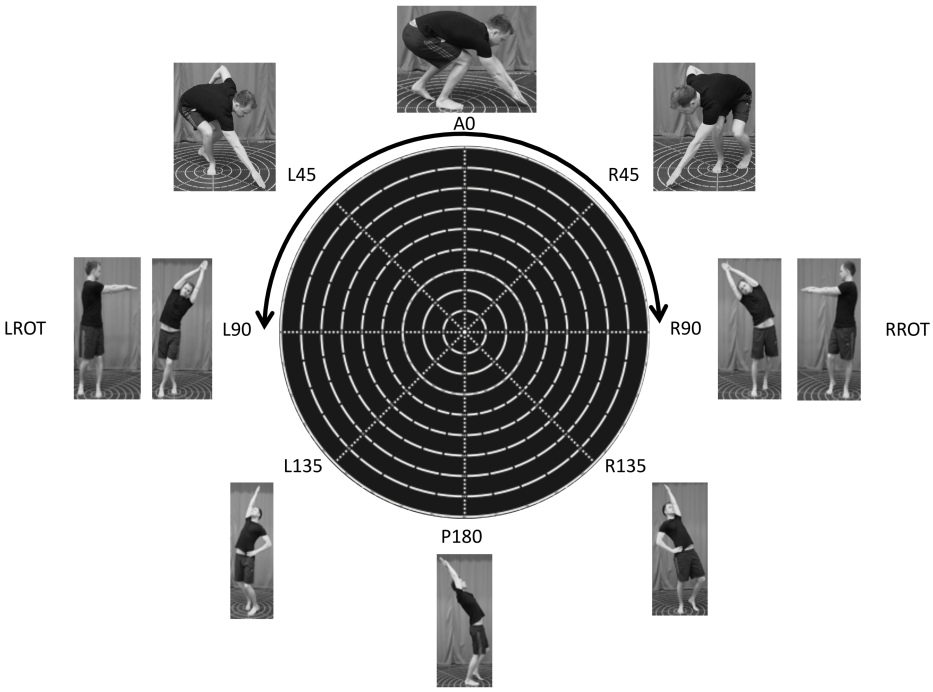

Figure 2. Maximum HSEBT reach positions. *Testing mat with reach directions and images showing maximum reach positions on the left foot.*

Starting position

Since we wanted to impose joint mobility demands on one lower extremity at a time, the position of both the stance and support foot had to be defined. To avoid the variable stance foot positions currently used in the SEBT (Plisky et al., 2009) standardization of stance foot positioning was defined as follows: 1) half of the foot should be in front of the line connecting the L90 and R90 reach directions and 2) the second toe and the center of the heel should be on top of the line connecting the A0 and P180 reach directions. The position of the support foot is also important since it can be used in a balancing strategy, which was observed in the unilateral hand reach test (the cross-over reach test) presented by Kivlan and co-workers (Kivlan et al., 2013). To avoid counterbalancing, toe-touch weight-bearing of the support foot at a 135-degree angle relative to the reach direction was chosen. This was to make sure that the BOS in the reaching direction did not increase. Furthermore, the support foot was angled in the direction of the reach (neutral position) to avoid any influence on the reach measurement, as lower extremity positioning has been shown to influence postural control and trunk biomechanics (Zhou, Ning, Hu, & Dai, 2016). Also, the support foot was positioned between the 20 and 30 cm concentric circle to approximate hip width. The only exceptions to these general support foot guidelines were the rotational reaches (LROT and RROT), where both feet were placed in parallel (on the L90 or R90 line) and the support foot was allowed to rotate in the direction of the reach, and in the L90 and R90 reaches, where the support foot was angled in the A0 direction.

Movement

The different reaches were defined based on hand(s) performing the reach with the following stance foot constraints: 1) the heel, big and little toe (first and fifth metatarsophalangeal joints) had to maintain ground contact during the reach, and 2) no footwear. Tests were divided into bilateral and unilateral hand reaches in order to facilitate uni- and multi-dimensional joint mobility demands respectively. Specifically, the three cardinal planes were targeted by bilateral hand reaches as follows: 1) sagittal (A0 and P180 reach), frontal (L90 and R90) and transverse plane (LROT and RROT) and defined as pure plane reaches. In the bilateral hand reaches the middle fingers were positioned on top of each other to decrease frontal and transverse plane joint movement contributions. The other horizontal reaches (L45, R45, L135 and R135) are all unilateral and defined as diagonal hand reaches. In these reach directions the hand selected to perform the reach was based on proprioceptive neuromuscular facilitation principles of crossing the midline; i.e. the right hand reaches to the L45 and L135 targets and vice versa. Similar movement patterns to the unilateral hand reaches have been advocated in shoulder rehabilitation (Kibler & Sciascia, 2016; McMullen & Uhl, 2000). During the diagonal reaches the opposite hand is positioned on the hip. This standardization is important considering that the SEBT preferred testing procedure is hands at the side (pelvis) (Gribble et al., 2012), which is not always abided by (Hertel, Miller, & Denegar, 2000; Plisky et al., 2009). For all reaches elbow(s) are extended with wrist(s) in neutral position(s). The verbal instructions given to the participant are: “reach as far as you can while maintaining balance”.

Testing order

A specific testing order was created to decrease testing time and to facilitate qualitative left-to-right comparisons. We decided that the general order should be left to right stance foot reaches to limit instructions to 10 left stance foot reaches, and asking the participant to perform the same reach on the right foot. In addition, this order will make immediate left to right qualitative comparisons easier. Furthermore, the overall testing order starts with horizontal reaches based on the hypothesized elicited hip joint movements (Table 2). Specifically, flexion movement patterns are performed first and ordered from external to internal hip rotation (L45, A0 to R45). Then, lateral reaches ordered from hip abduction to adduction (L90 to R90) followed by posterior (L135, P180 to R135) and rotational reaches (RROT to LROT) ordered from external to internal hip rotation. The testing order is presented in Appendix V.

Measurements and data presentation

Measurements are obtained from the maximum reach position from the center of the mat to the tip of the middle finger(s) (cm) for the horizontal reaches. For the rotational reaches the measurement is the angular excursion from A0 (0°) to maximum reach position. The best of three reaches after a minimum of three practice trials is used. Specifically, the L45, A0 and R45 the measurements are obtained from the finger position on the mat since ground level is the target, but only tapping on the mat without support is allowed for a valid trial. For the other horizontal (L90, R90, L135, P180 and R135) and the rotational reaches (LROT and RROT) the maximum reach position of the middle finger(s) is projected onto the mat using a plumb-line or stick. Loss of balance while reaching or the inability to return to the starting position is regarded as an incomplete attempt. All procedures have to be followed for the reach to be counted as a valid. A complete description of testing procedures is presented in Appendix V.

HSEBT results are presented as individual reach measurements, different composite scores as commonly done for the SEBT (Gribble et al., 2012), or area calculations. For ease of communication with patients and athletes we explored area calculations to provide a better visualization of scores and to present a “movement sphere”.

Joint mobility demands

While creating these tests the group hypothesized about the joint mobility demands imposed by the different reaches. The joint movements identified with bold letters have larger contributions (magnitude), those in regular font have smaller contributions, and “none” is used when the group was uncertain or felt that a specific joint movement contribution would be minimal (Table 2). Only left stance foot tests are described, since we expected right stance foot tests to be the same.

Table 2. *Joint movements targeted by the different HSEBT reach tests*

Joint	Plane of motion	Joint movements	R45	A0	L45	L90	R90	L135	P180	R135	RROT	LROT
Ankle	Sagittal	DF / PF	**DF**	**DF**	**DF**	DF	DF	**DF**	**DF**	**DF**	DF	PF
	Frontal	Ev / Inv	**Ev**	Ev	**Inv**	**Ev**	**Ev**	**Ev**	Ev	**Inv**	**Ev**	**Inv**
	Transverse	Abd / Add	**Abd**	Abd	Add	Abd	Abd	Abd	Abd	Add	**Abd**	**Add**
Knee	Sagittal	Flex / Ext	**Flex**	**Flex**	**Flex**	Flex	Ext	Flex	Flex	Ext	None	None
	Frontal	Abd / Add	Abd	Abd	Abd	Abd	Add	Abd	Abd	Add	Abd	Add
	Transverse	IR / ER	ER	IR	IR	IR	ER	ER	None	IR	ER	**IR**
Hip	Sagittal	Flex / Ext	**Flex**	**Flex**	**Flex**	Flex	Ext	**Ext**	**Ext**	**Ext**	None	None
	Frontal	Abd / Add	Abd	Add	Add	**Abd**	**Add**	Abd	None	**Add**	Abd	Add
	Transverse	IR / ER	**ER**	IR	**IR**	None	None	**ER**	None	**IR**	**ER**	**IR**
Trunk	Sagittal	Flex / Ext	**Flex**	**Flex**	**Flex**	None	None	**Ext**	**Ext**	**Ext**	None	None
	Frontal	Lat flex	Ipsi lat flex	Ipsi lat flex	Ipsi lat flex	**Ipsi lat flex**	**Contra lat flex**	**Ipsi lat flex**	None	Contra lat flex	Contra lat flex	Ipsi lat flex
	Transverse	Rot	Contra rot	Ipsi rot	Ipsi rot	None	None	**Contra rot**	None	Ipsi rot	**Contra rot**	**Ipsi rot**
Shoulder	Sagittal	Flex / Ext	Flex	**Flex**	**Flex**	**Flex**	**Flex**	**Flex**	**Flex**	**Flex**	Flex	Flex
	Frontal	Abd / Add	None	None	None	**Abd**	**Abd**	Abd	Abd	Abd	None	None
	Transverse	IR / ER	IR	IR	IR	None	None	ER	None	None	None	None
		Hor abd / Hor add	**Hor Add**	Hor Add	**Hor Add**	None	None	None	None	None	**Hor add**	**Hor add**

Note: DF = Dorsiflexion; PF = Plantarflexion; Ev = Eversion; Inv = Inversion; Abd = Abduction; Add = Adduction; Flex = Flexion; Ext = Extension; IR = Internal rotation; ER = External rotation; Lat flex = Lateral flexion; Rot = Rotation; Hor abd = Horizontal abduction; Hor add = Horizontal adduction; Ipsi = Ipsilateral; Contra = Contralateral.

Criterion related validity

Since there is no gold-standard dynamic postural control test there is no single criterion that the HSEBT measurements can be compared to. However, concurrent validity, one component of criterion related validity, can be determined by comparing the visually obtained maximum hand reach measurement to a gold standard measurement, such as motion capture data. This approach was used for the comparative SEBT (Bastien et al., 2014a).

Construct validity

A comparison of the HSEBT to a similar test, such as the SEBT, can be used to address construct validity. The level of agreement between specific SEBT and HSEBT reaches can be used to determine whether they assess the same parts (convergent validity) or different parts (divergent validity) of the underlying construct (dynamic postural control).

Reliability

Reliability is a fundamental characteristic of any test, which describes whether the measurement is consistent and free from error, and is commonly described as test-retest, intra- and inter-rater reliability. Test-retest reliability describes the consistency of measurements on two separate occasions. Intra-rater reliability refers to the consistency of measurements by the same tester in tests that follow each other within a short time interval, while inter-rater reliability describes the agreement between two different testers who measure the same group of participants and observe the same participant responses. It may be difficult to determine inter-rater reliability for the HSEBT since testing procedures require direct instructions by the tester, and some of the measurements (stick and plumb-line) are obtained in close interaction with the participant. Furthermore, a minimum of 120 reaches are done in one session (three trials for both familiarization and measurements). Thus, the best strategy to assess inter-rater reliability might be to perform testing on separate days. Based on the possible influence of fatigue, intra-rater reliability may also be difficult to assess.

Factors influencing reach measurements

Comparable SEBT foot reach measurements are influenced by factors such as anthropometry, age, activity level and sex. Specifically, leg length was found to explain a significant portion of the variance in the SEBT reaches (range R^2: .02 to .23) (Gribble & Hertel, 2003). Consequently, foot reaches have since mostly been normalized (% leg length). Physical activity also influence SEBT measures; specifically, differences between sports have been observed (Bressel, Yonker, Kras, & Heath, 2007), with equivocal findings between athletes and recreationally active individuals (Ambegaonkar et al., 2013; Sabin, Ebersole, Martindale, Price, & Broglio, 2010; Thorpe & Ebersole, 2008). Furthermore, both sex (Gorman, Butler, Rauh, Kiesel, & Plisky, 2012; Gribble & Hertel, 2003; Gribble, Robinson, Hertel, & Denegar, 2009; Holden, Boreham, Doherty, Wang, & Delahunt, 2016) and age influence SEBT reach measurements (Gonzalo-Skok, Serna, Rhea, & Marin, 2017; Holden et al., 2016; McCann et al., 2017). Based on these findings it appeared reasonable to explore the effect of these factors on the HSEBT outcome measurements.

HSEBT and athletic performance

Application of the HSEBT described previously may improve the assessment of athletic performance, especially in sports where the hands are important in performance, as in overhead sports (i.e. throwing and tennis). Overhead throwing is fundamental to sports such as baseball, cricket, javelin, volleyball, and team handball, and is a result of sequential muscle activation and torque generation in the kinetic chain that progresses in a proximal to distal sequence (Mero, Komi, Korjus, Navarro, & Gregor, 1994; Putnam, 1993; Roach, Venkadesan, Rainbow, & Lieberman, 2013; Young, 1996). The ability to generate high joint angular velocities in throwing is dependent on internal torques acting on joints with sufficient mobility for acceleration and deceleration of the movement. Roach and Lieberman explored the impact of mobility on throwing performance using bracing (Roach & Lieberman, 2014). Limiting proximal segmental mobility decreased joint power generation throughout the kinetic chain, angular velocities, elastic storage of energy at the shoulder, and throwing velocity. Thus, unrestricted joint movements are important for generating high throwing velocities. In overhead team handball throwing, specific upper extremity and trunk contributions to throwing velocity have been established (Hirashima et al., 2007; Hirashima, Yamane, Nakamura, & Ohtsuki, 2008; van den Tillaar & Ettema, 2004, 2007; Wagner, Pfusterschmied, von Duvillard, & Muller, 2011). However, traditional ROM measurements of upper extremity joint movement only (Schwesig et al., 2016; van den Tillaar, 2016) have been reported to have non-significant relationships to throwing velocity, which may be due to their aforementioned shortcomings. Thus, the HSEBT may be an appropriate test to assess dynamic postural control of joint movements associated with overhead throwing performance.

Purpose

In light of the current literature of dynamic postural control and functional mobility tests there is a need for a test that imposes joint mobility demands on the kinetic chain, such as the HSEBT. The specific aims of the thesis were to:

- Quantify the joint mobility demands imposed by the HSEBT
- Determine the validity of HSEBT measurements.
- Determine the reliability of HSEBT measurements.
- Determine the influence of HSEBT measurements on overhead athletic performance.
- Determine the influence of anthropometric measurements, sex, age and level of physical activity on HSEBT measurements.

Methods

Participants

In total, 224 participants volunteered to participate in one or more of the studies included in this thesis (Table 2). Studies I and II included recreationally active males, while study IV included national- and international-level female team handball players. Study III included international-level male and female youth athletes from different winter sports, who participated in a recent Youth Olympic Winter Games (YOG).

In studies I and II, participants were recruited from the student population at the Norwegian School of Sport Sciences and through the personal networks of the researchers conducting the studies. In study III participants were recruited in the Learn & Share area during the YOG, while elite female team handball players were recruited at the Norwegian Olympic and Paralympic Committee and Confederation of Sports, and from Elite Division clubs in the Oslo region (study IV).

Exclusion criteria for studies I, II and III were no current diagnoses impacting musculoskeletal function and no past surgeries to the trunk, lower or upper extremities. Exclusion criteria for all studies included any injuries in the past six months that led to loss of sports or recreational activity participation for more than seven days, and pain during testing.

In study II one participant withdrew due to LBP. In study IV one participant did not complete the protocol while one participant experienced pain while being tested and was consequently removed from the analysis. In total 222 participants were included in all studies with the distribution between studies as presented in Table 3.

Table 3. *Participant characteristics*

Study	Purpose	Paper	n	Sex	Age (years)	Height (cm)
I	Validity	I, II & III	28[a]	Male	23.8±2.2	189.7±6.0
II	Reliability	I & III	29	Male	23.8±2.2	180.0±9.3
III	Factors influencing HSEBT measurements	III	154	Male (76)	17.2±0.5	175.1±7.1
				Female (78)	17.0±0.7	165.9±5.9
IV	Application to team handball throwing performance	III & IV	11	Female	21.7±1.8	174.9±6.8

Note: [a]a subset of 20 subjects who were tested for both HSEBT and SEBT is reported in paper II

Ethics

All studies were conducted in accordance with Good Clinical Practice and the Declaration of Helsinki, using standard procedures routinely used in research settings at the Norwegian School of Sport Sciences. The protocols, written information and consent forms were submitted to the regional committee for medical and health research ethics for studies I to IV. The committee concluded that the studies were outside their mandate. Consequently, all studies were conducted according to Norwegian Law. All studies were approved by the Norwegian Center of Research Data (Appendix VI).

Prior to participation and signing an informed consent all participants were informed about the risks associated with the study. During the development of the HSEBT testing procedures we found that some participants reported some discomfort in terms of general soreness in the hips, lower back and thoracic spine after testing, which subsided within 24 hours. This could be due to HSEBT being a maximum reach test. Consequently, in all studies the participants were informed that this could be a potential response and that the maximum reach should be based on their own capacity. Since study III included YOG participants, verbal instructions were given in Norwegian and English with written information available in the following languages: Norwegian, Chinese, English, French, Japanese, German, Korean and Russian. In studies I-III no general warm-ups beyond familiarization with the reaches themselves were done. However, in study IV on throwing performance, speed and accuracy, a standardized warm-up was done since this was a maximum effort involving a high-velocity movement. The warm-up consisted of a general 10-minute warm-up followed by a handball-specific section that concluded with 2-3 throws at maximum effort (see Appendix VII for details). Overall, the risks of participating in these studies were considered low and not greater than what would be experienced during everyday sporting or recreational activity.

During data collection and analysis each subject was represented only by a code. Lists linking participants to codes were locked in a safe and destroyed at the end of data analyses.

Experimental approach

The present thesis consists of four studies with observational designs. Concurrent validity of HSEBT measurements was assessed by comparing visually obtained hand reach measurements to those calculated from motion capture data. Furthermore, the content validity of joint mobility demands, and the three-dimensional joint movements of the ankle, knee, hip, trunk and shoulder at the maximum reach position were calculated from motion capture data. Construct validity was obtained by comparing SEBT and HSEBT reach measurements (study I). Then, test-retest and inter-rater reliability was established by three different testers who tested participants individually on four different occasions (Study II). The influence of age, sex, level of physical activity and anthropometric measures on HSEBT outcome measurements were explored in study III, while the influence of HSEBT measurements on overhead team handball throwing performance was explored in study IV. Studies I,II and IV were conducted in the biomechanics laboratory at the Norwegian School of sport sciences, while study III was conducted at the facilities of a recent Youth Winter Olympic Games (YOG).

Equipment and variables

Motion capture

In studies I and IV a standard motion capture system was used (Qualisys Oqus 400 cameras, Qualisys AB, Gothenburg, Sweden). In study I a 15-camera set-up was used to measure the position of a full-body marker set. The cameras had different vertical positions (wall and tripods) to ensure that they could capture markers in anterior and posterior positions on the body in flexion and extension movement patterns, respectively. In study IV a 5-camera set-up was used to measure athlete entry and ball throwing speed in an overhead handball throw. The recording frequency used for both studies was 480 Hz. Prior to data acquisition the system was calibrated (20-30 seconds as recommended by the manufacturer) using an L-shaped reference frame (for the 750 wand kit) with four reflective markers, which defined the direction of the lab coordinate system, and a T-shaped wand (749.2 mm) with two reflective markers. A re-calibration was performed if 1) one of the cameras was identified as failed by the Qualisys Track Manager (QTM) software; 2) the average of the residuals of the position of the camera to the origin of the coordinate system was too high (>3 millimetres); and 3) if the T-shaped wand was subjectively judged to have not adequately covered the recording volume. In study I the approximate recording volume was 2.5 m (length and width) and 3 m (height), while in study IV it was 6 m (length), 4 m (width) and 3 m (height).

Video capture

In study III a Basler acA2000 – 165uc video camera (Baser AG, Ahrensburg, Germany) was used to measure the accuracy of team handball throws at 165 frames per second (study IV). Specifically, the camera was placed behind the participant, perpendicular to the target at a distance of 12 m and a height of 2 m.

Other equipment

Anthropometric measurements of height and mass were obtained using a Seca model 217 stadiometer and a Seca flat scale, respectively (Seca GmbH. & Co. Hamburg, Germany). A standard tape measure was used for the other anthropometric measurements. Leg length was measured as the distance from the greater trochanter to the floor for one leg. Arm length was measured from the acromion to the middle digit with the shoulder abducted to 90° for one arm, and wingspan was measured from middle digit to middle digit with both shoulders abducted to 90°.

All HSEBT reach measurements were obtained using the testing mat (Athletic Knowledge Nordic AB, Stockholm, Sweden) as described previously. Measurements for the lateral, extension and rotational movement patterns required the use of a plumb-line and a wooden stick.

Data acquisition

Validity (study I)

Due to differences in SEBT testing procedures (Gribble et al., 2012; Hertel et al., 2000; Plisky et al., 2009) some clarification of how these reach measurements were obtained is needed. The SEBT was performed as follows: 1) the stance foot was placed on the middle of the mat; 2) the heel, first and fifth metatarsal heads maintained ground contact during the reaches; 3) the trunk was aligned with the reach vector for diagonal reaches (R45, R135,L135 and L45; 4) the lateral reaches (R foot L90 and L foot R90 reach) were performed with the reaching foot in front of the stance foot; 5) both hands were on the hips; and 6) during rotational reaches the big toe of the reaching foot followed the 50 cm radius circle with the longitudinal axis of the foot segment oriented toward the center of the testing mat. The SEBT rotational reaches are new and were added to target dynamic postural control in the transverse plane in single leg stance and to compare measurements to the HSEBT rotational reaches. Prior to performing each reach test the subjects were asked to stand with their feet parallel to the shoulder line, with the hands on the hips, for a minimum of 3 seconds. For all HSEBT and SEBT reaches a minimum of three practice trials were allowed, after which three valid maximum reaches were recorded with the highest value used for analysis. Trials were discarded if procedures were not followed.

Fifty-eight spherical reflective markers (20 mm Ø) were attached over specific anatomical landmarks using bi-adhesive tape in order to define and track the foot, leg, thigh, pelvis, thorax and upper arm segment (Figure 3). A complete list of markers used is provided in Appendix VIII. Marker clusters for the leg, thigh and upper arm were attached firmly using tensoplast elastic tape (BSN Medical GmBH, Hamburg, Germany).

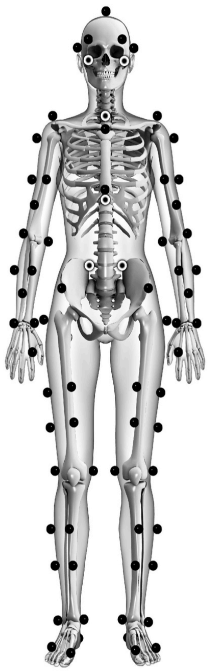

Figure 3. Marker set study I

Reliability (study II)

Each participant completed the HSEBT in four sessions across four different days. One of three raters (convenience sample) administered the HSEBT independently each day, thus one rater administered the HSEBT twice. The rater who tested all participants twice was a physical therapist with two years' experience in administering the HSEBT, while the other two raters were sports science students with one year of experience. The order of raters was randomized for each participant, while the order of reaches was the same for all sessions (Appendix V). Testing sessions for each participant were scheduled at the same time of day when possible; 8 a.m.–12 noon (morning) or 12 noon –6 p.m. (afternoon), since time of day has been found to influence performance on the SEBT (Gribble, Tucker, & White, 2007).

Factors influencing HSEBT reach performance (study III)

Participants were tested on a subset of the HSEBT due to the time constraints of testing as many athletes as possible in a short time span while they were available for testing at the

YOG. Specifically, two flexion (L45 and R45) extension (L135 and R135) and rotational (LROT and RROT) reaches were tested for both feet.

Application to team handball throwing performance (study IV)

Specific HSEBT reaches were selected based on the similarity of elicited hip, trunk and shoulder joint positions and movements (study I) to the different phases of the overhead team handball throw (van den Tillaar & Ettema, 2007; Wagner et al., 2011). Specifically, the L135 and R135 reaches were tested since hip, trunk and upper extremity joint movements and positions assumed in these reaches (study I) are similar to those observed in the cocking and acceleration phase (van den Tillaar & Ettema, 2007; Wagner et al., 2011). The L45 and R45 reaches were tested since hip, trunk and upper extremity positions and joint movements assumed in these reaches (study I) are similar to those observed in the follow-through phase of the throw (van den Tillaar & Ettema, 2007; Wagner et al., 2011). The LROT and RROT rotational reaches were done to target the hip and trunk rotations associated with the three phases of the throw (van den Tillaar & Ettema, 2007; Wagner et al., 2011).

The throwing target was indicated on a high-jump mat (2 m x 3 m) placed vertically in front of a handball goal in order to protect lab equipment. Based on previously used protocols in handball throwing studies, sports tape was used to define a +-shaped mark centrally located inside a 1 m x 1 m throwing target (van den Tillaar & Ettema, 2003; Wagner et al., 2014). For right-handed subjects the target was placed 0.1 m below the crossbar at the right side of the goal's midline and mirrored for the left-handed subjects (van den Tillaar & Ettema, 2003). An International Handball Federation standard size women's handball (Select AS, Glostrup, Denmark) was used for all throws. A three-step run-up throw from 8 m was allowed, since this throw is frequently used in team handball when throwing from the backcourt position (Wagner, Pfusterschmied, Von Duvillard, & Muller, 2012). All subjects were given the following instructions: "Throw the ball as hard as you can and hit the target" (van den Tillaar & Ettema, 2003). There was a one-minute rest period between throws. The subjects continued throwing until five valid throws (i.e. the ball landed inside the target) were achieved, and the total number of throws was recorded.

Kinematic data was obtained using two markers attached to the ball (two markers opposite each other to determine the center of the ball), throwing hand (head of the intermediate phalanx of the third digit) and the pelvis (highest point left and right iliac crest). A complete description of the lab set-up is presented in Figure 4.

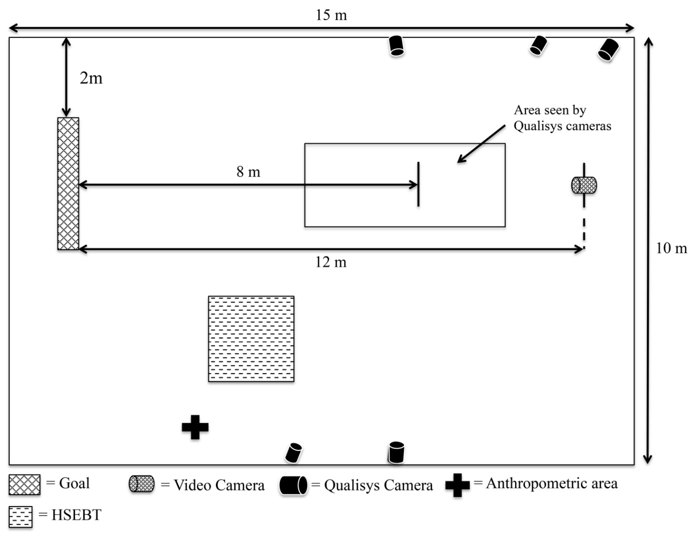

Figure 4. *Laboratory set-up study IV (Sæland, 2015)*

Data processing

Validity (study I)

Markers were identified using the QTM software. If gaps in marker trajectories occurred they were interpolated or reconstructed using Matlab (Mathworks Inc, Natick, MA, USA) (Federolf, 2013). However, for very long gaps these methods failed and the affected joint angles, hip, spine or shoulder, could not be calculated. All kinematic data for the HSEBT reaches presented in study I are based on a minimum of 24 subjects. Marker data was not filtered.

Data analysis was done using Visual 3D® (C-Motion Inc., Rockville, MD, USA). Marker locations were registered in a static standing trial in order to determine the static calibration of the kinematic model. Local coordinate systems for the different segments were created based upon established recommendations from the International Society of Biomechanics (Wu et al., 2002; Wu et al., 2005). Specifically, the following segments were created: 1) foot based on the recommendation of Hamill and co-workers (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014); 2) leg (Wu et al., 2002); 3) thigh using the prediction approach to calculate the hip joint center (Bell, Brand, & Pedersen, 1989; Wu et al., 2002); 4) pelvis (Leardini et al., 2011; Wu et al., 2002); 5) thorax (Leardini et al., 2011; Wu et al., 2005); and 6) upper arm (Wu et al., 2005). Joint rotations of the ankle (foot and leg segment), knee (leg and thigh segment), hip (thigh and pelvic segment) and spine (pelvic and thoracic segment) were calculated (cardan sequence XYZ) in the sagittal (X-axis), frontal (Y-axis), and transverse (Z-axis) planes. Shoulder motions were calculated using both ZYZ (Z_{first}=horizontal adduction and abduction, Y=abduction and adduction, Z_{third}=internal and external rotation) (Wu et al., 2005) and XYZ (X=flexion and extension only) cardan sequences. No upper arm segments were created, nor were any shoulder joint movements calculated for the SEBT reaches.

Joint movements were calculated as the difference between starting (φ_{start}) and maximum reach position (φ_{max}). Specifically, starting positions were defined as the mean joint positions observed during the last 95 of the first 100 frames of recording (Equation 1).

$$\varphi_{start} = \text{mean}_{\text{frames } 5\text{-}100} \quad (1)$$

Maximum reach position (φ_{max}) was defined as the maximum or minimum x, y and z-coordinate values in the global coordinate system (orientations: *x* (+) anterior, *y* (+) right lateral and *z* (+) vertical) of the second metacarpal and the first metatarsal marker of the reaching hand(s) or foot, respectively. Specifically, the maximum positions (φ_{max}) for the HSEBT reaches were defined as follows: flexion (minimum *z*-coordinate value), lateral (minimum and maximum *y*-coordinate values), extension (minimum *z*-coordinate value except P180 reaches where the minimum *x*-coordinate value was used) and rotational movement patterns (minimum x-coordinate value). The maximum position (φ_{max}) for the SEBT reaches were defined as follows: diagonal reaches (maximum value of √(x-coordinate^2 + y-coordinate^2), P180 (minimum x-coordinate), A0 (maximum x-coordinate), L90 (minimum y-coordinate), R90 (maximum y-coordinate) and rotational reaches (minimum x-coordinate). All tests were visually inspected to ensure that the set criteria matched for φ_{max}. Then, joint movements (θ) were calculated (Equation 2) for each reach and averaged for all subjects.

$$\theta = \varphi_{max} - \varphi_{start} \quad (2)$$

Joint movements of mirrored reaches (left and right) were averaged and named based on left stance foot definitions for ease of data presentation. For HSEBT reaches with bilateral symmetrical shoulder joint movements, i.e. A0, P180, L90 and R90 reaches, the mean of left and right shoulders is presented. To compare the magnitude of joint movements elicited by both the HSEBT and SEBT, the greatest values in joint movements (θ_{max}) of the ankle, knee, hip, trunk and shoulder were identified for the HSEBT ($\theta_{maxHSEBT}$) and SEBT ($\theta_{maxSEBT}$) reaches and their differences were calculated ($\theta_{maxDIFF}$) (Equation 3).

$$\theta_{maxDIFF} = \theta_{maxHSEBT} - \theta_{maxSEBT} \tag{3}$$

Then, $\theta_{maxHSEBT}$ and $\theta_{maxSEBT}$ values were compared to determine whether they were within a 95% confidence interval of normative ROM reference (Greene & Heckman, 1994), except for knee rotations. Trunk movements (lumbar and thoracic spine values added) were compared to the lowest reported values (Magee, 2006). Comparisons of $\theta_{maxHSEBT}$ and $\theta_{maxSEBT}$ ankle and knee abduction and adduction were not done since these measures are not commonly quantified using clinically available assessment tools and normative clinical ROM values are lacking (Greene & Heckman, 1994). Shoulder $\theta_{maxHSEBT}$ comparisons to normative values were done for flexion, abduction, external rotation (Greene & Heckman, 1994) and horizontal adduction (Magee, 2006) only. Thus, eighteen joint movements (ankle, knee, hip and trunk) were compared for both HSEBT and SEBT, with the addition of four shoulder joint movements for the HSEBT.

Further comparisons between the HSEBT and SEBT reach measurements were done using composite scores and area calculations. As indicated previously, our clinical experience supports the idea that expressing test outcomes as areas provides a better visual feedback of results to participants than composite scores. Therefore, both areas and composite scores were used in the analysis. Total area (A_{tot}) was calculated as the sum of the areas covered by the eight triangles obtained from the horizontal reach (HR) measurements (HR_i (i= 1(A0), 2(R45), 3(R90), 4(R135), 5(P180), 6(L135), 7(L90) and 8(L45)) (Equation 4). Additionally, anterior (A_{ant}) (Equation 5) and posterior areas (A_{post}) (Equation 6) were calculated in order to differentiate between anterior and posterior HSEBT and SEBT reaches. Composite scores (CS) were also calculated since they have been used to quantify combinations of SEBT reaches (Plisky et al., 2006). Specifically, CS were calculated as the sum of all (CS_{tot}), anterior (CS_{ant}), and posterior reaches (CS_{post}) (Equations 7-9).

$$A_{tot}=\sum 1/2*HR_{1\text{-}8}*HR_{1\text{-}8}*\sin 45° \quad (4)$$

$$A_{ant}=\sum 1/2*HR_{1\text{-}3,7\text{-}8}*HR_{1\text{-}3,7\text{-}8}*\sin 45° \quad (5)$$

$$A_{post}=\sum 1/2*HR_{3\text{-}7}*HR_{3\text{-}7}*\sin 45° \quad (6)$$

$$CS_{tot}=\sum HR_{1\text{-}8} \quad (7)$$

$$CS_{ant}=\sum HR_{1,2,8} \quad (8)$$

$$CS_{post}=\sum HR_{4\text{-}6} \quad (9)$$

In order to determine similarities of movement strategies between specific HSEBT and SEBT reaches, shared movement synergies were quantified as the number of common joint movements (maximum 12) used to obtain the maximum reach position. The movement synergy was defined as follows: strong (>8), moderate (5 to 8) and weak (<5).

Concurrent validity of HSEBT reaches was established by comparing visually obtained HSEBT reach measurements (Max_m) to those calculated from kinematic data (Max_{kin}). Based on the φ_{max} definitions previously described, horizontal reach distances Max_{kin} were calculated from the position of the metacarpal marker at the maximum reach event resolved in the coordinate system of the stance foot. Specifically, Max_{kin} was quantified as $|x|$ and $|y|$ (pure plane reaches) and $\sqrt{(x^2 + y^2)}$ (diagonal reaches). An underestimation of Max_{kin} relative to Max_m is expected for horizontal reaches since the foot coordinate system is not exactly aligned with the center of the testing mat, and the position of the 5th metacarpal marker underestimates the position of the distal-most point of the third digit. Max_{kin} for rotational reaches was defined as the orientation (°) (first rotation (Z) of the ipsilateral upper arm segment) at the maximum reach event resolved in the local coordinate system of the stance foot.

Reliability (study II)

Raters were blinded to the results since all HSEBT measurements were sent to a fourth researcher for data aggregation, storage and analysis.

Factors influencing HSEBT (study III)

No specific data processing beyond recording reach measurements was necessary for this study.

Application to team handball throwing performance (study IV)

Different composite scores (CS) were calculated as the sum of horizontal reaches (HR_i (i= 1(L45), 2(R45), 3(R135), 4(L135)) as follows: dominant and non-dominant foot (CS_{dom}, $CS_{non-dom}$) (Equation 10), dominant and non-dominant foot flexion movement patterns (CS_{dom_ant}, $CS_{non-dom\_ant}$) (Equation 11) and dominant and non-dominant foot extension movement patterns (CS_{dom_ant}, $CS_{non-dom\_ant}$).

$$CS_{dom,\ non-dom}=\sum HR_{1-4} \tag{10}$$

$$CS_{dom\_ant,\ non-dom\_ant}=\sum HR_{1,2} \tag{11}$$

$$CS_{dom\_post,\ non-dom\_post}=\sum HR_{3,4} \tag{12}$$

Marker data was filtered (2nd order Butterworth low pass filter with 15Hz cut-off frequency). Throwing velocity ($m \cdot s^{-1}$) was then calculated as the average velocity between frames 3 and 8 after time (t_0) (frame of maximum acceleration between the marker on the third digit) of the center of the ball (midpoint between the two ball markers) (van den Tillaar & Ettema, 2007). Entry velocity ($m \cdot s^{-1}$) was defined as the maximum velocity of the midpoint between the two pelvic markers at 3 and 100 milliseconds prior to t_0. Both throwing and entry velocity were calculated for all throws using Matlab (Mathworks Inc, Natick MA, USA). Accuracy of all throws was calculated from video as mean radial error, the average of five throws of the absolute distance from the center of the ball to the center of the target (van den Tillaar & Ettema, 2003), using Dartfish (Dartfish, Fribourg, Switzerland).

Statistical analysis

For all studies descriptive statistics (mean and standard deviation (SD)) were calculated in Excel for Mac OS 10.10.5 (Apple Inc., Cupertino, CA, USA), version 14.4.8 (Microsoft Corp., Redmond, WA, USA), while all other statistical tests were done using IBM SPSS version 21.0 (IBM, Armonk, NY, USA). Normality of the data was assessed using the Shapiro-Wilk test

($p<0.05$). Outliers were determined using the outlier labelling rule of 2.2 multiples of the upper and lower quartiles (Hoaglin & Iglewicz, 1987) and were removed from the analysis (study I-IV). Correlation coefficients were interpreted as follows: 0.00 - 0.25 little or no relationship, 0.25 – 0.50 fair, 0.50 – 0.75 moderate to good, and 0.75 – 1.00 good to excellent (Portney & Watkins, 1993). Effect sizes were calculated in studies I and III and interpreted as follows: <0.2=small; 0.2 to 0.5=medium; >0.8=large effect (J. Cohen, 1988).

Validity (study I)

The relationships between HSEBT and SEBT areas, composite score and specific reach tests were obtained using linear regression analysis. To determine the differences between $\theta_{maxHSEBT}$ and $\theta_{maxSEBT}$ two-sided paired t-tests (level of confidence α>95%) were used with a subsequent calculation of Cohen´s *d* effect sizes.

The criterion related (concurrent) validity of HSEBT reaches was determined by comparing Max_m to Max_{kin} using linear regression analysis and the Bland Altman method. The difference score (Max_{diff}) was calculated (Equation 13) and in the presence of a non-normal distribution a ratio of manual to kinematic measurements was calculated (Equation (14)) and used in the subsequent analysis. Bland Altman plots were generated for Max_{diff} or r_{m_kin} (*y*-axis) and the average of measurements (Equation (15)) (*x*-axis). Bias between measurements ($Max_{diffmean}$) was calculated (Equation (16)) with standard deviation (Max_{diffSD}) and plotted with a 95% confidence interval ($Max_{diffmean} \pm 1.96 Max_{diffSD}$). Then standard error difference scores were calculated (Equation (17)).

$$Max_{diff} = Max_m - Max_{kin} \quad (13)$$

$$r_{m\_kin} = Max_m / Max_{kin} \quad (14)$$

$$Max_{mean} = mean(Max_{kin} + Max_m) \quad (15)$$

$$Max_{diffmean} = mean_{subject1-28} Max_{diff} \quad (16)$$

$$SE_{diff} = \sqrt{}(Max_{diffSD}^2/n) \quad (17)$$

Reliability (study II)

Inter-rater and test–retest reliability were assessed for each test by calculating intraclass correlation coefficients, $ICC_{2,3}$ and $ICC_{2,1}$ respectively. The following criteria were used to evaluate ICC values: ≥0.90 high, 0.80–0.89 moderate and below 0.80 questionable (Vincent, 2005). Test–retest and inter-rater SDs were calculated using Equations (18) and (19) respectively. Stability of measurements was assessed by calculating the SEM (Equation (20)), and the CV for both test–retest (Equation (21)) and inter-rater reliability (Equation (22)). Minimal detectable change (MDC_{95}) was calculated using a 95% confidence interval for both test–retest and interrater reliability (Equation (23)). A within-subjects repeated-measures analysis of variance (ANOVA) was performed with the independent variable being day (1, 2, 3, 4) to identify whether any learning effects had occurred between sessions. The same ANOVA analysis was done with the independent variable being rater (1, 2, 3), where the first session of the rater who tested the subjects twice was used. The level of significance was set at 95% ($\alpha = 0.05$).

$$SD_{test\text{-}retest} = \sqrt{\sum(\text{test } 1 - \text{test } 2)^2/2n} \quad (18)$$

$$SD_{interrater} = \sqrt{\sum(SD_{between\ raters})^2/n - 1} \quad (19)$$

$$SEM = SD \times \sqrt{(1 - ICC)} \quad (20)$$

$$SD_{test\text{-}retest}/\text{pooled mean} \times 100 \quad (21)$$

$$SD_{interrater}/\text{pooled mean} \times 100 \quad (22)$$

$$MDC_{95} = 1.96 \times \sqrt{(2 \times SEM)} \quad (23)$$

Factors influencing HSEBT reach performance (study III)

Mirrored reach test measurements on the left and right foot were compared using a paired samples t-test and interpreted using effect size (Cohen's d) and MDC values (study I). The influence of anthropometric measures (height, wingspan, arm length, leg length and trunk), age, sex and level of physical activity (athletes; recreational) on HSEBT measurements was determined using stepwise multiple regression analysis. Measurements for the same tests on the left and right foot (e.g. left foot R45 reach and right foot L45 reach) were averaged. Linearity was assessed by visual inspection of scatter plots of studentized residuals and predicted values. Multicollinearity was assessed using a variable inflation factor (VIF) with a cut-off of >10. Independence of residuals was analyzed using Durbin-Watson statistics with cut-off values <1 and >3. Homoscedasticity was assessed by visual inspection of the scatter plots of the standardized predicted values of the model and the standardized residuals.

Normality of residuals was determined by visual inspection of the histograms of standardized residuals and probability-probability plots. Casewise diagnostics were set to three standard deviations to determine whether 1% or less of the subjects had standardized residuals outside this distribution. Specifically, a random sample, consisting of 75% of the participants, was used to generate the initial model using forward stepwise regression based on statistical significance (t-test). The model was then validated on the remaining 25% of the participants using forced entry. The validation model was then compared to the initial model based on change of R^2 values, and independent variables that significantly contributed ($p<.05$) to the model were retained. Pearson correlation coefficients of retained variables from the regression analysis to their respective HSEBT reaches were then calculated. The criterion for normalization of HSEBT reaches to anthropometric measures was based on significant correlation coefficients and R^2 values and changes greater than the CV of the respective reach (study I).

Independent samples t-tests were then used to explore differences between age groups (young:<20 years; adult: >20 years), sex (M; F) and level of physical activity (recreational; athletes). Homogeneity of variance was assessed using Levene´s test. In the case of non-normal distribution of data as indicated by a significant Shapiro-Wilk test outcome, the test z-scores of both skewness and kurtosis were calculated to explore the necessity for data transformation. Effect size was calculated using Cohen´s *d*.

Application to team handball throwing performance (study IV)

Pearson correlation analysis (two-tailed) was carried out to determine the relationship between throwing velocity, accuracy, number of attempts and HSEBT reach measurements (cm, ° and CS). Linearity of the relationships between these variables was assessed using visual inspection of the scatter plots. Dynamic postural control tests are presented based on the dominant foot (the opposite of the throwing hand). Since 9 of 11 players were left-foot dominant, left-foot reach definitions were used for the presentation of the HSEBT results.

Results

Validity of the HSEBT (Study I)

Content validity

A detailed description of the joint movements used to estimate maximum reach position for the different HSEBT reaches is presented in Table 5. HSEBT anterior reaches resulted in ankle dorsiflexion (range = 19.4 to 29.7°), knee flexion (range = 81.6 to 101.7°), hip flexion (range = 98.8 to 103.3°) and trunk flexion (range = 51.2 to 58.8°), while posterior reaches elicited ankle dorsiflexion (range = 19.7 to 24.5°), knee flexion (range = 18.0 to 28.8°), hip extension (range = 17.4 to 29.5°) and trunk extension (range = 28.5 to 36.2°). HSEBT lateral reaches targeted different frontal plane movements where the L90 reach generated ankle inversion (7.5±4.5°), knee abduction (2.1±3.7°), hip abduction (16.9±6.3°) and ipsilateral trunk flexion (38.2±7.0°), whereas the R90 reach elicited ankle eversion (18.2±3.3°), knee adduction (2.7±3.0°), hip adduction (27.6±6.4°) and contralateral trunk flexion (38.8±5.8°). HSEBT rotational reaches targeted different transverse plane movements where the LROT reach induced ankle adduction (15.1±5.2°), knee internal rotation (15.1±3.7°), and hip internal rotation (33.2±3.8°), whereas the RROT reach elicited ankle abduction (13.4±3.6°), knee external rotation (23.8±5.4°), hip external rotation (29.5±5.4°) and contralateral trunk rotation (33.7±4.5°). Shoulder extension, adduction, internal rotation and horizontal abduction are not reported since no test specifically targeted the magnitude of these joint movements. Movement synergies ranged from 4/12 to 10/12 joint movements (Table 5).

Table 5. *Content validity joint movements elicited by HSEBT reaches*

Reach	Plane of motion	Ankle θ (°)	Knee θ (°)	Hip θ (°)	Trunk θ (°)	Shoulder θ (°)	Movement synergy
A0	Sag	DF:26.2±4.5 (**DF**)	Flex:101.7±16.0^a (**Flex**)	Flex: 103.3±19.8 (**Flex**)	Flex: 58.8±9.7^a (**Flex**)	Flex: 112.9±11.3 (**Flex**)	8/12
	Front	Ev:12.9±5.8 (**Ev**)	Add: 13.2±7.8 (Abd)	Abd: 1.0±7.4 (Add)	Ipsi lat flex: 4.1±4.5 (**Ipsi lat flex**)		
	Trans	Abd:6.1±3.2 (**Abd**)	IR: 12.9±10.4 (**IR**)	ER: 1.7±5.5 (IR)	Ipsi rot: 0.9±3.6 (**Ipsi rot**)		
R45	Sag	DF: 29.7±5.7^a (**DF**)	Flex: 88.3±32.3 (**Flex**)	Flex: 108.2±7.9^a (**Flex**)	Flex: 51.2±6.8 (**Flex**)	Flex: 117.7±11.5 (**Flex**)	10/12
	Front	Ev: 12.5±4.7 (**Ev**)	Add: 17.2±6.5^a (Abd)	Abd: 16.0±6.3 (**Abd**)	Contra lat flex: 1.2±6.3 (Ipsi lat flex)		
	Trans	Abd: 11.5±4.0 (**Abd**)	ER: 6.1±7.9 (**ER**)	ER: 2.2±8.0 (**ER**)	Contra rot: 15.2±5.3 (**Contra rot**)	ER: 36.4±18.8; Hor add: 63.7±9.2 (IR, **Hor add**)	
R90	Sag	DF: 8.6±7.5 (**DF**)	Flex: 6.6±13.6 (Ext)	Ext: 0.5±11.2 (**Ext**)	Ext: 14.0±10.8 (None)	Flex: 127.9±14.6 (**Flex**)	9/12
	Front	Ev: 18.2±3.3^a (**Ev**)	Add: 2.7±3.0 (**Add**)	Add: 27.6±6.4^a (**Add**)	Contra lat flex: 38.8±5.8^a (**Contra lat flex**)	Abd:127.9±13.8* (**Abd**)	
	Trans	Abd: 2.1±3.4 (**Abd**)	IR: 1.6±3.8 (ER)	IR: 2.1±6.0 (None)	Contra rot: 9.3±5.8 (None)		
R135	Sag	DF: 19.7±5.7 (**DF**)	Flex: 18.0±10.6 (Ext)	Ext: 17.4±5.2 (**Ext**)	Ext: 28.5±9.7 (**Ext**)	Flex: 149.8±14.4 (**Flex**)	7/12
	Front	Ev: 5.2±4.7 (Inv)	Abd: 1.7±2.2 (Add)	Add: 12.1±5.2 (**Add**)	Contra lat flex: 20.6±8.0 (**Contra lat flex**)		
	Trans	Add: 0.6±4.5 (**Add**)	IR: 8.0±3.8 (**IR**)	IR: 10.4±6.0 (**IR**)	Ipsi rot: 2.3±8.0 (**Ipsi rot**)	ER: 49.2±23.5 (None)	
P180	Sag	DF: 24.5±6.4 (**DF**)	Flex: 21.1±10.2 (**Flex**)	Ext: 28.3±5.6 (**Ext**)	Ext: 36.2±7.2^a (**Ext**)	Flex: 144.3±13.0 (**Flex**)	8/12
	Front	Ev: 0.8±2.6 (**Ev**)	Abd: 1.6±2.4 (**Abd**)	Add: 2.9±3.8 (None)	Contra lat flex: 3.2±3.6 (None)		
	Trans	Abd: 4.7±2.4 (**Abd**)	IR: 2.8±3.4 (None)	ER: 3.7±4.0 (None)	Contra rot: 1.8±2.8 (None)		
L135	Sag	DF: 23.0±8.0 (**DF**)	Flex: 28.8±14.0 (**Flex**)	Ext: 29.5±6.8^a (**Ext**)	Ext: 33.9±9.7 (**Ext**)	Flex: 150.6±15.8^a (**Flex**)	6/12
	Front	Inv: 5.3±4.4 (Ev)	Abd: 1.8±3.4 (**Abd**)	Abd: 10.4±6.0 (**Abd**)	Ipsi lat flex: 18.3±7.9 (**Ipsi lat flex**)		
	Trans	Abd: 10.2±3.0 (**Abd**)	ER: 5.2±5.1 (**ER**)	ER: 20.4±5.5 (**ER**)	Contra rot: 2.7±8.9 (**Contra rot**)	ER: 50.3±25.5^a (**ER**)	
L90	Sag	DF: 9.1±9.3 (**DF**)	Flex: 21.6±24.5 (**Flex**)	Flex: 8.3±23.8 (**Flex**)	Ext: 14.8±12.9 (None)	Flex: 130.6±12.6 (**Flex**)	4/12
	Front	Inv: 7.5±4.5^a (Ev)	Abd: 2.1±3.7 (**Abd**)	Abd: 16.9±6.3^a (**Abd**)	Ipsi lat flex: 38.2±7.0^a (**Ipsi lat flex**)	Abd: 129.5±13.8^a (**Abd**)	
	Trans	Abd: 0.0±3.4 (**Abd**)	IR: 0.1±4.9 (**IR**)	IR: 4.3±13.5 (None)	Ipsi rot: 11.2±9.0 (None)		
L45	Sag	DF: 19.4±8.2 (**DF**)	Flex: 81.6±20.6 (**Flex**)	Flex: 98.8±8.2 (**Flex**)	Flex: 57.4±10.2 (**Flex**)	Flex: 107.6±11.4 (**Flex**)	10/12
	Front	Inv: 1.1±5.0 (**Inv**)	Add: 6.2±6.9 (Abd)	Add: 15.2±5.5 (**Add**)	Ipsi lat flex: 11.0±6.7 (**Ipsi lat flex**)		
	Trans	Add: 8.2±4.9 (**Add**)	IR: 12.4±6.7 (**IR**)	IR: 2.1±6.0 (**IR**)	Ipsi rot: 15.3±4.4 (**Ipsi rot**)	ER: 30.4±12.7;Hor add: 76.2±14.7 (IR, **Hor add**)	
LROT	Sag	DF: 0.7±5.2^a (PF)	Flex: 12.8±7.5 (None)	Flex: 10.8±5.8 (None)	Ext: 6.8±7.9 (None)		10/12
	Front	Inv: 5.9±5.0 (**Inv**)	Abd: 5.5±1.9^a (Add)	Add: 9.8±3.7 (**Add**)	Ipsi lat flex: 7.4±5.6 (**Ipsi lat flex**)		
	Trans	Add: 15.1±5.2^a (**Add**)	IR: 15.1±3.7^a (**IR**)	IR: 26.9±5.1^a (**IR**)	Ipsi rot: 33.2±3.8^a (**Ipsi rot**)	Hor Add: 132.8±10.7^a (**Hor add**)	
RROT	Sag	DF: 10.0±5.5 (**DF**)	Flex: 6.7±11.7^a (None)	Ext: 2.6±6.0 (None)	Ext: 2.8±8.2 (None)		8/12
	Front	Ev: 5.9±3.4 (**Ev**)	Add: 3.8±2.6 (Abd)	Add: 0.7±5.1 (Abd)	Contra lat flex: 7.2±5.5 (**Contra lat flex**)		
	Trans	Abd: 13.4±3.6^a (**Abd**)	ER: 23.8±5.4^a (**ER**)	ER: 29.5±5.4^a (**ER**)	Contra rot: 33.7±4.5^a (**Contra rot**)	Hor Add: 134.2±13.9^a (**Hor add**)	

Note: L = Left; R = Right; A0 = Anterior reach; R45 = Right anterolateral (45°) reach; R90 = Right lateral (90°) reach; R135 = Right posterolateral (135°) reach; P180 = Posterior (180°) reach; L135 = Left posterolateral (135°) reach; L90 = Left lateral (L90) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach; Sag = Sagittal plane; Front = Frontal plane; Trans = Transverse plane; DF = Dorsiflexion; PF = Plantarflexion; Ev = Eversion; Inv = Inversion; Abd = Abduction; Add = Adduction; Flex = Flexion; Ext = Extension; ER = External rotation; IR = Internal rotation; Ipsi = Ipsilateral; Contra = Contralateral; Lat flex = Lateral flexion; Rot = Rotation; Hor add = Horizontal adduction; ^{a}= $\theta_{maxHSEBT}$ (maximum joint movement HSEBT). Hypothesized joint movements from Table 2 are identified in parentheses with bold font representing agreement between the hypothesized and observed joint movements.

The identified $\theta_{maxHSEBT}$ exhibited greater values than $\theta_{maxSEBT}$ for all joint movements, except for ankle dorsiflexion, plantarflexion and knee extension (Table 6). Joint movements with greater $\theta_{maxHSEBT}$ (bold font column 5 Table 6) values were significantly greater than $\theta_{maxSEBT}$ for all comparisons, except for hip external rotation ($t(34)=-0.51$, $p=.61$, $d=.09$), with effect sizes ranging from medium to large (d = .39 to 5.21). The $\theta_{maxSEBT}$ values were significantly greater than $\theta_{maxHSEBT}$ for all ankle dorsiflexion, plantarflexion and knee extension with effect sizes ranging from medium to large (d = .45 to 1.39). Comparisons of $\theta_{maxHSEBT}$ and $\theta_{maxSEBT}$ to normative ROM values revealed that 8/22 and 3/18 joint movements, respectively, were within normative ROM values (Table 6).

Table 6. *Maximum joint movements of HSEBT and SEBT with comparisons to normative ROM*

Joint	Plane	Joint Movement	Reach	$\theta_{maxHSEBT}$ (°)	Reach	$\theta_{maxSEBT}$ (°)	t-test	Cohen´s *d*	Normative ROM	HSEBT comparison	SEBT comparison
Ankle	Sag	DF	R45	29.7±5.7	R45	32.5±5.1	t(38)=5.95 p<.01	.95	26.1±6.5[e]	x	x
		PF	LROT	-0.7±5.2	L90	2.3±3.4	t(39)=2.91, p<.01	.45	40.5±8.1[e]		
	Front	Ev	R90	**18.2±3.3**	L90	12.2±3.8	t(39)=-9.46, p<.01	1.50	21±5[e]	x	x
		Inv	L90	**7.5±4.5**	LROT	-0.9±5.7	t(38)=-8.00, p<.01	1.28	37±4.5[e]		
	Trans	Abd	RROT	**13.4±3.6**	R45	10.8±2.4	t(38)=-5.45, p<.01	.87	NR	NA	NA
		Add	LROT	**15.1±5.2**	LROT	10.6±4.7	t(38)=-5.57, p<.01	.89	NR	NA	NA
Knee	Sag	Flex	A0	**101.7±7**	R90	77.1±12.6	t(39)=-9.08, p<.01	1.44	141±5.3[e]		
		Ext	RROT	-6.7±11.7	L90	8.7±4.8	t(38)=8.67, p<.01	1.39	2±3[e]	x	x
	Front	Abd	LROT	**5.5±1.9**	LROT	2.6±2.4	t(38)=-7.79, p<.01	1.25	NR	NA	NA
		Add	R45	**17.2±6.5**	P180	11.0±6.8	t(39)=9.04, p<.01	1.43	NR	NA	NA
	Trans	IR	LROT	**15.1±3.7**	LROT	13.7±4.8	t(38)=2.45, p=.019	0.39	20[f]		
		ER	RROT	**23.8±5.4**	RROT	16.5±5.2	t(37)=-9.73, p<.01	1.58	30[f]		
Hip	Sag	Flex	R45	**108.2±7.9**	P180	93.8±8.8	t(39)=-13.37, p<.01	2.11	121±6.4[e]	x	
		Ext	L135	**29.5±6.8**	LROT	-9.2±8.4	t(36)=25.92, p<.01	4.26	12±5.4[e]	x	
	Front	Abd	L90	**16.9±6.3**	RROT	5.9±7.7	t(37)=7.59, p<.01	1.23	41±6[e]		
		Add	R90	**27.6±6.4**	L90	23.3±7.4	t(38)=2.95, p<.01	0.47	27±3.6[e]	x	
	Trans	IR	LROT	**26.9±5.1**	LROT	19.2±5.4	t(37)=10.91, p<.01	1.77	44±4.3[e]		
		ER	RROT	**29.5±5.4**	RROT	27.2±7.1	t(34)=-0.51, p=.61	.09	44±4.8[e]		
Trunk	Sag	Flex	A0	**58.8±9.7**	R135	17.0±13.7	t(38)=-18.53, p<.01	2.97	60[f]		
		Ext	P180	**36.2±7.2**	L90	5.1±8.7	t(38)=-18.03, p<.01	2.88	45[f]		
	Front	Lat flex	L90 and R90	**38.4±6.4[a]**	LROT	5.9±7.2	t(38)=-29.43, p<.01	5.21	35[f]	x	
	Trans	Rot	LROT and RROT	**33.4±4.2[b]**	LROT	7.6±6.9	t(38)=-21.32, p<.01	3.41	38[f]		
Shoulder	Sag	Flex	L135	**150.6±15.8**	NA	NA			167±4.7[e]		
	Front	Abd	L90 and R90	**128.7±12.8[c]**	NA	NA			184±7[e]		
	Trans	ER	L135	**50.3±25.5**	NA	NA			104±8.5[e]		
		Hor Add	LROT and RROT	**133.5±12.3[d]**	NA	NA			130[f]	x	

Note: Bold font identify $\theta_{maxHSEBT} > \theta_{maxSEBT}$; L = Left; R = Right; A0 = Anterior reach; R45 = Right anterolateral (45°) reach; R90 = Right lateral (90°) reach; R135 = Right posterolateral (135°) reach; P180 = Posterior (180°) reach; L135 = Left posterolateral (135°) reach; L90 = Left lateral (L90) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach; Sag = Sagittal plane; Front = Frontal plane; Trans = Transverse plane; DF = Dorsiflexion; PF = Plantarflexion; Ev = Eversion; Inv = Inversion; Abd = Abduction; Add = Adduction; Flex = Flexion; Ext = Extension; ER = External rotation; IR = Internal rotation; Ipsi = Ipsilateral; Contra = Contralateral; Lat flex = Lateral flexion = Rot, Rotation = Hor add, Horizontal adduction; [a] Average trunk lateral flexion L90 and R90 reach; [b] Average trunk rotation LROT and RROT reach; [c] Average shoulder abduction L90 and R90 reach; [d] Average shoulder horizontal adduction LROT and RROT reach; [e] Reference value from Greene and Heckman (Greene & Heckman, 1994); [6] Reference value from Magee (Magee, 2006).

Criterion related validity

Excellent correlations were observed between Max_m and Max_{kin} measurements for 18 out of the 20 tests ($r \geq 0.90$), with a shared variance that ranged from 81 to 97%. Two tests, left foot RROT ($r = 0.89$) and right foot RROT ($r = 0.79$), had good correlations and a shared variance of 79% and 63% respectively (Table 7). Max_{diff} was normally distributed as assessed by a Shapiro-Wilk test with one exception, right foot P180 reach ($p = 0.045$); however, r_{m_kin} for this test was normally distributed ($p = 0.067$) and used in the agreement analysis (Table 7 and Figure 5). There was a positive fixed bias ($Max_{diffmean}$) for all horizontal reaches ranging from 2.2 to 12.8 cm and 23.7% (P180). Fixed biases for the rotational reaches were positive for ipsilateral (10.2 and 11.2°) and negative for contralateral rotational reaches (−5.0 and −6.0°) (Table 7 and Figure 5).

Table 7. *Concurrent validity of the HSEBT*

						Regression analysis		Agreement analysis	
Test	Foot	Hand(s)	Order	Max_m (±SD)[a]	Max_{kin} (±SD)[a]	r	R^2	Bias±SD	Bias±SE
A0	L	B	9	72.8±8.4	70.6±6.9	0.97	0.94	2.2±2.4	2.2±0.5
A0	R	B	15	71.2±9.9	67.8±8.4	0.98	0.96	3.4±2.3	3.4±0.5
R45	L	L	1	79.0±7.2	74.1±6.6	0.95	0.90	4.9±2.4	4,9± 0.4
L45	R	R	5	79.2±8.4	74.1±6.9	0.96	0.93	5.1±2.6	5.1±0.5
R90	L	B	12	67.4±11.2	55.3±10.5	0.96	0.92	12.0±3.1	12.0±0.6
L90	R	B	18	67.6±12.3	54.7±11.1	0.95	0.91	12.8±3.8	12.8±0.7
R135	L	L	4	62.0±13.3	52.2±12.3	0.95	0.89	9.8±4.4	9.8±0.8
L135	R	R	8	61.3±14.3	50.2±14.3	0.99	0.97	11.1±2.4	11.1±0.5
P180	L	B	10	71.3±12.9	58.5±12.4	0.97	0.94	12.8±3.1	12.8±0.6
P180	R	B	16	70,8±12.4	57.7±11.9	0.95	0.91	1.237±0.087[b]	1.237±0.016[b]
L135	L	R	2	87.6±8.9	76.6±8.6	0.95	0.91	11.0±2.7	11,0± 0.5
R135	R	L	6	82.8±10.7	73.1±9.9	0.94	0.88	9.7±3.7	9.7±0.7
L90	L	B	11	75.7±10.0	71.8±7.6	0.90	0.81	3.8±4.6	3.8±0.9
R90	R	B	17	74.5±11.6	69.5±9.5	0.95	0.90	5.1±4.0	5.1±0.8
L45	L	R	3	68.2±9.5	65.0±8.1	0.99	0.98	3.2±1.9	3.2±0.4
R45	R	L	7	65.7±9.9	63.0±8.6	0.98	0.96	2.7±2.3	2.7±0.4
RROT	L	B	14	135.4±14.8	140.4±16.0	0.89	0.79	-5.0±7.3	-5.0±1.4
LROT	R	B	20	140.8±15.1	146.8±19.4	0.90	0.81	-6.0±8.8	-6.0±1.7
LROT	L	B	13	133.3±18.7	123.1±18.9	0.92	0.84	10.2±7.7	10.2±1.5
RROT	R	B	19	135.2±15.5	124.0±16.3	0.79	0.63	11.2±10.3	11.2±2.0

Note: SD = Standard deviation; SE = Standard error; Max_m = Maximum observed reach HSEBT measurement; Max_{kin} = Maximum measured kinematic measurement; r = Correlation coefficient; R^2 = Coefficient of determination; L = Left; R = Right; A0 = Anterior reach; R45 = Right anterolateral (45°) reach; R90 = Right lateral (90°) reach; R135 = Right posterolateral (135°) reach; P180 = Posterior (180°) reach; L135 = Left posterolateral (135°) reach; L90 = Left lateral (L90) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach; [a] = cm is the unit in all reach tests with the exception of LROT and RROT (°); [b] = bias as ratio (r_{m_kin}=Ratio Max_m/Max_{kin}).

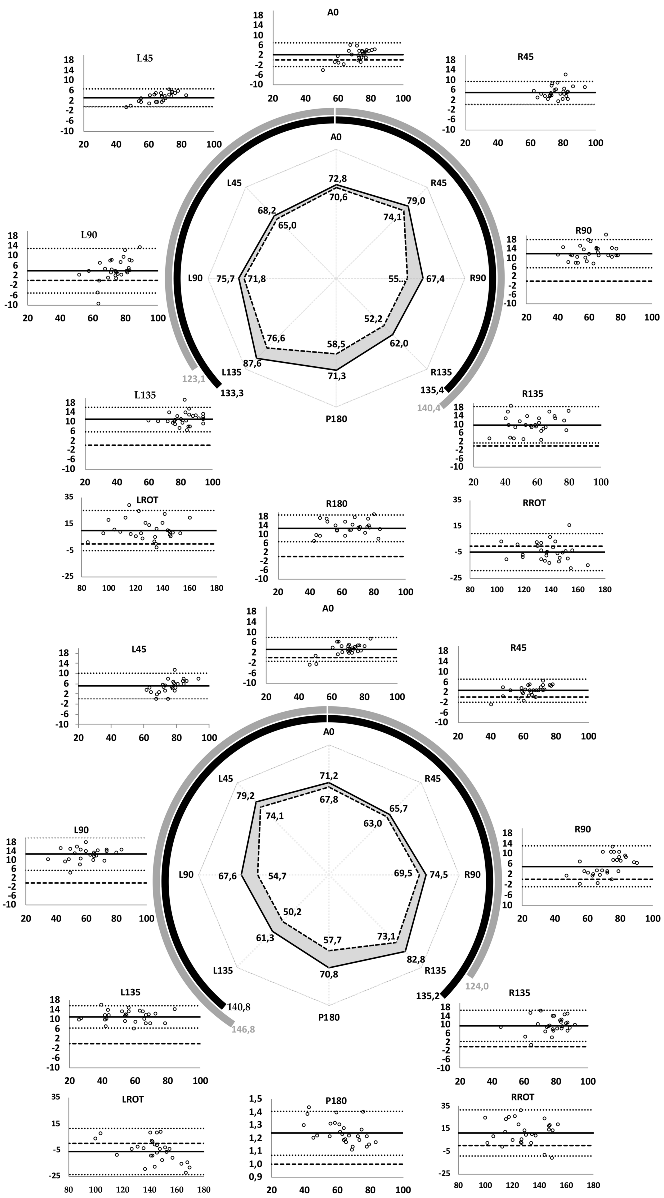

Figure 5. Agreement analysis of horizontal and rotational reaches, left and right foot. *Visual representation (center top and bottom) of horizontal reach test scores (full line Max_m, dotted line Max_{kin} and grey area showing difference). Circular graphs (Max_{kin} grey, Max_m black) of left and right rotational reaches. Bland Altman plots (y axis: Max_{diff} and x-axis: Max_{mean}) for all tests with fixed bias (full line) with 95% confidence interval (dotted line) and agreement (dashed line). Note that the units are cm for all reaches except LROT and RROT (°).*

Construct validity

HSEBT and SEBT reach measurements with correlations between area, composite scores and reach measurements are presented in Table 8 and Figures 6 and 7. Total area (A_{tot}) and composite score (CS_{tot}) correlations ranged from r=.393 to .606, with statistical significance for the right foot only (Table 8). Both A_{ant} and CS_{ant} had higher correlations (range r = .531 to .823) than A_{post} and CS_{post} (range r = .269 to .406) (Table 8). Anterior reaches, on both the left and right foot, had moderate to good correlations ranging from r = .515 to .572 and r = .707 to .822, respectively. None of the posterior reaches were significantly correlated (Figure 6). Anterior hand reach to posterior foot reach comparisons (A and CS) were significantly correlated (r=.534 to .698), while posterior hand reaches to anterior foot reaches (A and CS) were significantly correlated for the right foot only (r = .469 and r = .480) (Table 8). Variable correlations were observed for the lateral (range r = -.182 to .510) and rotational reaches (range r = .402 to .696) (Figure 6 and 7).

Table 8. *Area and composite score comparisons between HSEBT and SEBT*

	Left foot		Right foot	
Comparisons	**r**	**R^2**	**r**	**R^2**
A_{tot}	.393.	.154	.602**	.362
A_{ant}	.531*	.282	.780**	.608
A_{post}	.269	.072	.406	.165
HSEBT A_{ant} and SEBT A_{post}	.534*	.285	.698**	.487
HSEBT A_{post} and SEBT A_{ant}	.227	.052	.480*	.230
CS_{tot}	.414	.171	.606**	.367
CS_{ant}	.605**	.366	.823**	.677
CS_{post}	.341	.116	.344	.118
HSEBT CS_{ant} and SEBT CS_{post}	.536*	.287	.608**	.370
HSEBT CS_{post} and SEBT CS_{ant}	.261	.068	.469*	.220

Note: A_{tot} = Total area; A_{ant} = Anterior area; A_{post} = Posterior area; CS_{tot} = Total composite score; CS_{ant} = Anterior composite score; CS_{post} = Posterior composite score. Statistical significance denoted as: * p<0.05 and ** p<0.01.s

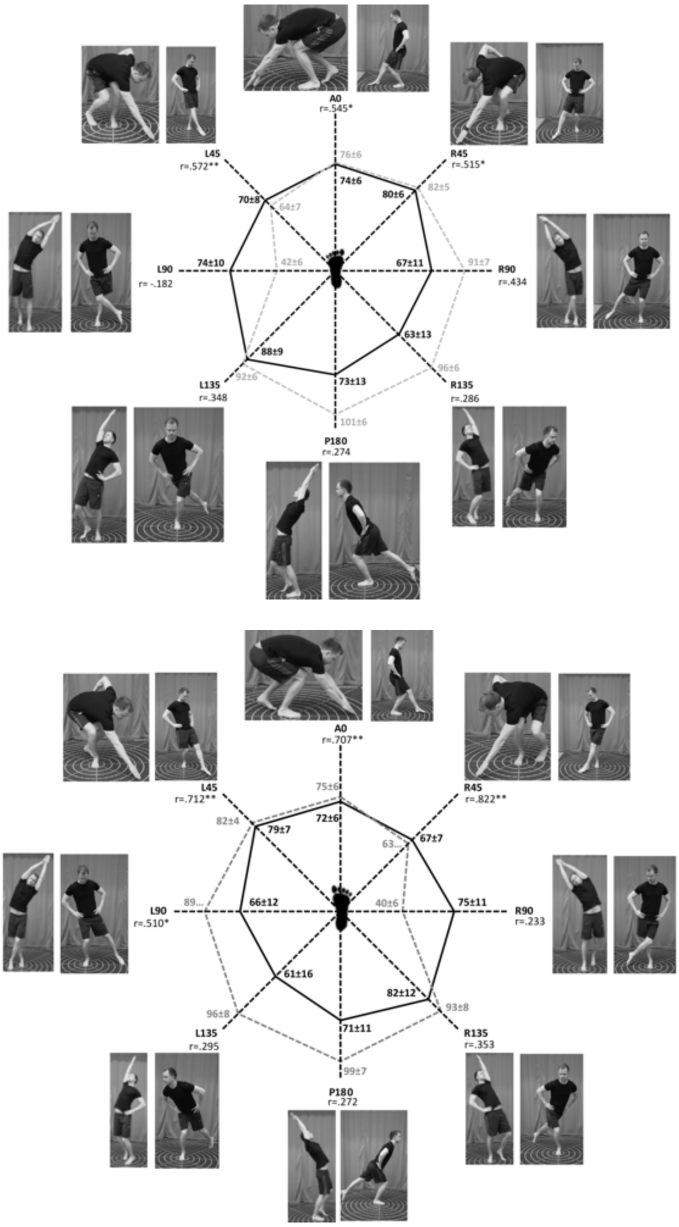

Figure 6. Horizontal reach comparisons for the HSEBT and SEBT on the left and right leg. *Visual representations of the execution of the horizontal reaches (photographs) and mean (±SD) reach distances (cm) observed for all tests in the center graphs for HSEBT (black) and SEBT (grey). Correlation coefficients (r) are shown for each direction (*p<0.05 and **p<0.01).*

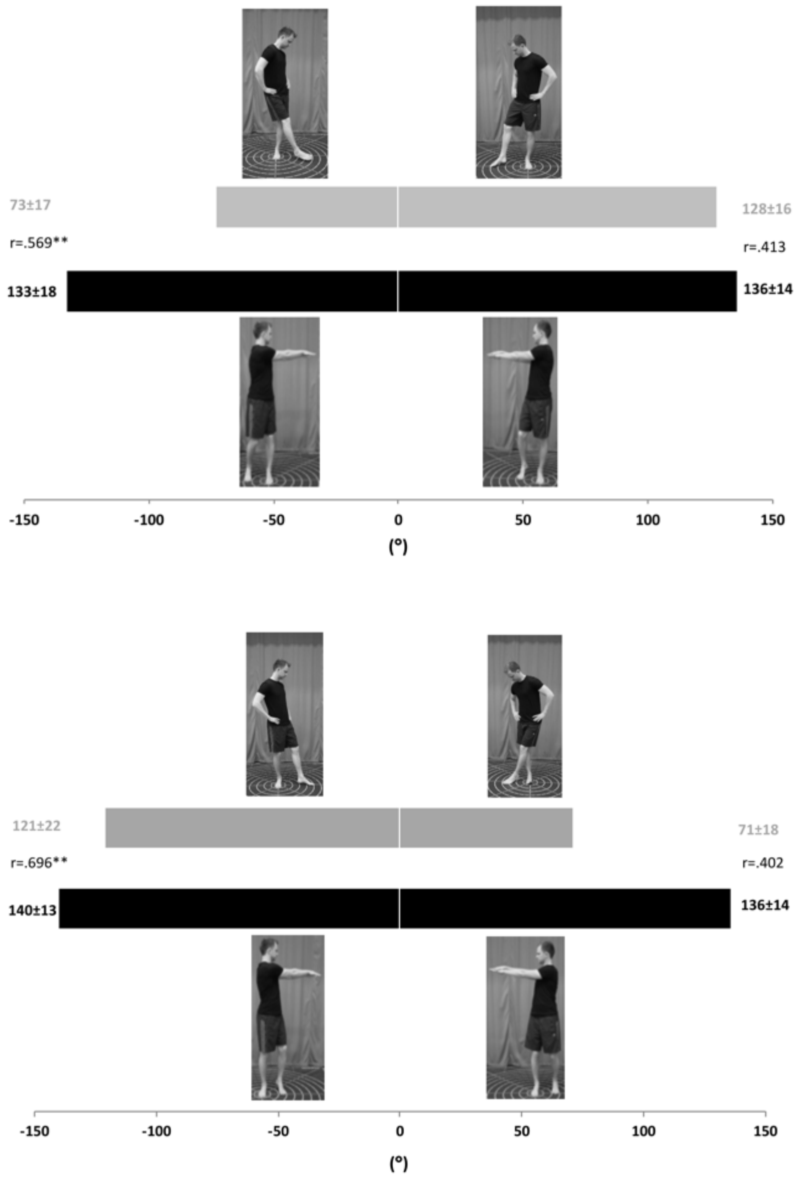

Figure 7. Rotational reach comparisons for the HSEBT and SEBT on the left and right leg. *Visual representation of the execution of the rotational reaches (photographs) for both left (top) and right leg (bottom) with mean (± SD) reach excursion (°) observed for all tests in the horizontal bar graphs for both HSEBT (black) and SEBT (grey). Correlation coefficients (r) are shown for each direction (*p<0.05 and **p<0.01).*

Reliability of the HSEBT (Study II)

There were 6.4 ± 6.1 days between test sessions, and 63.2% of consecutive test sessions were scheduled at the same time of the day (morning or afternoon). HSEBT reach measurements, ICC, SEM and CV for both interrater and test–retest reliability are presented in Table 9, where mirrored tests left and right follow each other and are grouped by color (grey and white). HSEBT reach measurements (mean ± SD) for the three and two sessions used for inter-rater and test-retest reliability respectively are also presented in Table 9.

Test–retest reliability was moderate to high for 19 out of 20 HSEBT reaches (range ICC = 0.80 to 0.96) with right foot L90 reach being questionable (ICC = 0.77). SEM ranged from 0.3 to 2.8 cm and 1.7 to 2.6° for horizontal and rotational reaches respectively, while CV ranged from 2.1 to 13.1%. MDC_{95} ranged from 0.9–7.9 cm and 4.7–7.2° for horizontal and rotational reaches, respectively (Table 9).

Inter-rater reliability was high (range ICC = 0.90 to 0.98) with SEM ranging from 0.3 to 2.1 cm and 1.8 to 2.4° for horizontal and rotational reaches respectively. CV values ranged from 3.1 to 14.6%, while MDC_{95} ranged from 0.9 to 5.7 cm and 5.1 to 6.6° for horizontal and rotational reaches, respectively (Table 9). No effect of test session (day) on the results was observed; however, a significant difference between raters was observed for the following tests (maximum difference between raters identified in parentheses): left foot A0 reach (1.4 cm); right foot L135 reach (5.6 cm); left foot L90 reach (2.6 cm); right foot LROT reach (6.9°); and L foot LROT reach (5.4°).

Table 9. *Test-retest and inter-rater reliability HSEBT*

				Test-retest reliability							Inter-rater reliability						
Test	Foot	Hand(s)	Order	Reach (±SD)[a]	ICC $_{2,1}$	95 CI	SD_{test_retest}	SEM[a]	CV	MDC_{95}[a]	Reach (±SD)[a]	ICC $_{2,3}$	95 CI	$SD_{interrater}$	SEM[a]	CV	MDC_{95}[a]
A0	L	B	3	72±8	0.96	0.92, 0.98	1.5	0.3	2.1	0.9	72±8	0.98	0.95, 0.99	2.2	0.3	3.1	0.9
A0	R	B	4	72±7	0.90	0.79, 0.95	2.3	0.7	3.2	2.1	73±8	0.97	0.95, 0.99	2.3	0.4	3.2	1.1
R45	L	L	1	79±7	0.85	0.71, 0.93	2.6	1.0	3.3	2.8	79±7	0.95	0.90, 0.97	2.9	0.6	3.6	1.8
L45	R	R	2	80±7	0.87	0.74, 0.94	2.4	0.9	3.0	2.4	80±7	0.95	0.90, 0.97	2.8	0.6	3.5	1.7
R90	L	B	9	68±10	0.82	0.65, 0.91	4.4	1.9	6.5	5.1	68±10	0.95	0.91, 0.98	3.8	0.8	5.6	2.3
L90	R	B	10	68±10	0.87	0.73, 0.94	3.9	1.4	5.8	3.9	68±11	0.95	0.91, 0.98	3.9	0.9	5.8	2.4
R135	L	L	15	50±13	0.80	0.61, 0.90	6.4	2.8	12.8	7.9	49±14	0.91	0.84, 0.96	6.6	2.0	13.4	5.5
L135	R	R	16	49±15	0.84	0.69, 0.92	6.5	2.6	13.1	7.2	50±14	0.92	0.85, 0.96	7.3	2.1	14.6	5.7
P180	L	B	13	67±12	0.87	0.74, 0.94	4.3	1.6	6.4	4.3	69±11	0.96	0.92, 0.98	3.9	0.8	5.7	2.2
P180	R	B	14	67±11	0.80	0.61, 0.90	5.1	2.3	7.6	6.3	67±11	0.93	0.88, 0.97	4.8	1.3	7.2	3.5
L135	L	R	11	80±12	0.87	0.74, 0.94	4.2	1.5	5.2	4.2	81±12	0.93	0.87, 0.97	5.4	1.4	6.6	3.9
R135	R	L	12	80±14	0.90	0.80, 0.95	4.5	1.4	5.6	3.9	80±13	0.95	0.90, 0.97	5.4	1.2	6.7	3.3
L90	L	B	7	73±10	0.84	0.69, 0.92	4.0	1.6	5.5	4.5	74±11	0.92	0.84, 0.96	5.2	1.4	7.0	4.1
R90	R	B	8	72±10	0.77	0.57, 0.89	4.8	2.3	6.6	6.3	74±11	0.93	0.86, 0.96	4.9	1.3	6.7	3.6
L45	L	R	5	65±9	0.94	0.87, 0.97	2.2	0.5	3.4	1.5	66±9	0.96	0.92, 0.98	3.3	0.7	5.0	1.8
R45	R	L	6	66±8	0.91	0.82, 0.96	2.5	0.8	3.8	2.1	66±9	0.95	0.91, 0.97	3.5	0,8	5.2	2.1
RROT	L	B	17	129±13	0.87	0.74, 0.94	4.7	1.7	3.6	4.7	128±14	0.92	0.85, 0.96	6.5	1.8	5.1	5.1
LROT	R	B	18	134±13	0.86	0.72, 0.93	5.0	1.9	3.8	5.2	130±13	0.90	0.81, 0.95	7.5	2.4	5.8	6.6
LROT	L	B	19	124±14	0.84	0.68, 0.92	5.7	2.3	4.6	6.3	121±15	0.93	0.86, 0.96	7.1	1.9	5.8	5.2
RROT	R	B	20	119±14	0.82	0.66, 0.91	6.1	2.6	5.1	7.2	118±16	0.93	0.88, 0.97	7.0	1.8	5.9	5.1

Note: [a] = cm is the unit in all reach tests with the exception of LROT and RROT where ° is the measurement unit; ICC = Intraclass correlation coefficient; SD=Standard deviation; SEM = Standard error of measurement (cm/°) ; CV = Coefficient of variation (%); MDC_{95} = Minimal detectable change; L = Left; R = Right; B = Bilateral; A0 = Anterior reach; R45 = Right anterolateral (45°) reach; R90 = Right lateral (90°) reach; R135 = Right posterolateral (135°) reach; P180 = Posterior (180°) reach; L135 = Left posterolateral (135°) reach; L90 = Left lateral (L90) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach.

Factors influencing HSEBT reach performance (study III)

Descriptive data for the different groups, sex, age and physical activity level, are presented in Table 10 with the significance of group differences, effect sizes and established MDC values from study II. The male group was older than the female group (*d*=.83), with greater anthropometric measures (range *d* = 0.94 to 1.51). The adult group also had greater anthropometric measures than the young group (range *d* = 0.56 to 1.17). Recreationally active participants were older than the athletes (*d* = 2.00), with greater anthropometric measures (range *d* = 0.64 to 1.26). Females, young participants and athletes demonstrated significantly greater normalized L45 and R45 reach measurements ($p \leq .001$) with medium effect sizes. Trivial effects were observed for the non-normalized comparisons for these reaches with one exception: males had greater R45 reach measurements than females (small effect) with a group difference greater than MDC values. Small to medium effects for sex, level of physical activity and age were observed for the R135 reach. Specifically, the athletic group had reach measurements greater than MDC values, while the observed difference between the young and the adult group (7.6 cm) was within the range of MDC values. The athlete group had significantly greater L135 reach measurements (4.1 cm) than the recreational group (small effect), which is within the range of MDC values. Trivial to small effects were observed for age, sex and level of physical activity of the rotational reach measurements (Table 10).

Table 10. *Age, anthropometry and HSEBT results (absolute and normalized values) grouped by sex, age and activity level with group comparisons*

	Male	Female	*d*	p	Young	Adult	*d*	p	Athletes	Recreational	*d*	p	MDC
n	133	90			159	64			166	57			
Age (yrs)	20.2±4.3	17.6±1.8	.83	<.001	17.1±.6	24.3±3.4	12.5	<.001	17.4±1.4	24.1±3.9	2.00	<.001	
Height (cm)	177.5±7.1	167.1±6.7	1.51	<.001	170.6±8.0	179.6±7.0	1.17	<.001	170.7±7.9	180.4±6.8	1.26	<.001	
Leg length (cm)	90.3±4.6	86.1±4.5	.94	<.001	87.5±4.6	91.2±5.0	.78	<.001	87.7±4.7	91.3±4.4	.79	<.001	
Wingspan (cm)	179.4±8.2	168.5±7.9	1.35	<.001	173.0±9.6	179.4±8.5	.68	<.001	173.0±9.6	180.2±8.1	.77	<.001	
Arm length (cm)	75.0±3.3	70.3±3.6	1.38	<.001	72.4±4.3	74.7±3.7	.56	<.001	72.4±4.3	75.0±3.4	.64	<.001	
R45 (cm)	80.1±6.4	78.4±5.8	.28	.043	79.3±6.0	79.4±6.3	.01	.942	79.4±5.9	79.4±6.9	.01	.928	1.5-2.1
R45 NORM (%)	44.7±2.9	46.5±2.8	.64	<.001	45.9±2.8	44.4±3.2	.50	.001	45.9±2.8	44.0±3.1	.66	<.001	NE
L45 (cm)	68.1±7.6	68.4±6.0	.04	.760	68.3±6.8	67.7±7.8	.08	.583	68.4±6.7	67.5±7.8	.13	.396	2.4-2.8
L45 NORM (%)	38.0±3.9	40.6±3.1	.72	<.001	39.6±3.5	37.7±4.0	.50	.001	39.7±3.5	37.2±3.9	.67	<.001	NE
L135 (cm)	85.6±9.6	87.3±7.8	.19	.181	87.0±8.7	84.9±8.7	.24	.110	87.5±8.2	83.4±9.6	.48	.003	3.9-4.2
R135 (cm)	60.7±13.3	65.3±9.7	.41	.004	64.5±11.6	56.9±14.6	.55	<.001	65.0±11.1	54.5±14.9	.75	<.001	7.2-7.9
LROT (°)	128.3±16.1	129.8±13.1	.10	.462	130.0±13.7	125.5±16.5	.31	.038	129.2±14.0	127.3±16.6	.12	.426	6.3-7.2
RROT (°)	134.4±13.1	133.1±10.5	.11	.431	134.8±11.1	132.6±14.0	.17	.211	134.9±11.3	134.7±14.1	.06	.679	4.7-5.2

Note: Values are means ± standard deviations; R45 = Right anterolateral (45°) reach; R135 = Right posterolateral (135°) reach; L135 = Left posterolateral (135°) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach; NORM = normalized HSEBT measurements; % = percentage of wingspan (reach measurement/wingspan·100); MDC = Minimal detectable change values from study II; NE = Not established.

In the stepwise regression analysis multicollinearity was not observed (range VIF = 1.000 to 4.152) and there was a homogeneity of variance (range Durbin-Watson = 1.699 to 2.397). Wingspan explained 34.6 and 11.7% of the variance in the R45 and L45 reach measurements, respectively. Leg length explained 1.9 and 2.7% of the R45 and L135 reach measurements respectively (Table 11). No anthropometric variable could explain a significant portion of the variance in the R135, LROT and RROT reaches. Based on the aforementioned criteria, only the L45 and R45 measurements were normalized to wingspan and expressed as a percentage of wingspan. In addition, sex explained 4.2 and 8.9% of the variation of the R45 and L45 measurements respectively. However, the contributions of sex and leg length to L45 and R45 reach measurements were non-significant in the validation model (Appendix IX). Level of physical activity explained 3.3% and 6.5% of the L135 and R135 reach measurements, respectively (Table 11).

Table 11. *Stepwise multiple linear regression of HSEBT tests*

Test	*B*	SE *B*	Β	R^2
R45 Step 1				
Constant	11.96	7.22		
Wingspan	.39	.041	.59***	.346
R45 Step 2				
Constant	-3.93	8.45		
Wingspan	.47	.047	.62***	
Sex	3.07	.92	.24***	.388 (ΔR^2= .042)
R45 Step 3				
Constant	.62	8.58		
Wingspan	.58	.069	.89***	
Sex	3.1	.90	.24***	
Leg length	-.279	.12	-.22*	.407 (ΔR^2= .019)
L45 Step 1				
Constant	22.71	9.69		
Wingspan	.26	.055	.34***	.117
L45 Step 2				
Constant	-3.86	11.13		
Wingspan	.40	.062	.53***	
Sex	5.15	1.21	.35***	.206 (ΔR^2= .089)
L135 Step 1				
Constant	87,38	.83		
Activity level	-3.86	1.67	-.18*	.033
L135 Step 2				
Constant	59.67	12.86		
Activity level	-4.64	1.69	-22**	
Leg length	.32	.15	.17*	.060 (ΔR^2=.027)
R135				
Constant	64.68	1.08		
Activity level	-7.21	2.17	-.25**	.065
RROT				
NE				
LROT				
NE				

Note: B = Unstandardized coefficient; β = Standardized beta coefficient; SE = Standard error; R^2 = Coefficient of determination; NE = No variables entered into the equation; R45 = Right anterolateral (45°) reach; R135 = Right posterolateral (135°) reach; L135 = Left posterolateral (135°) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach. Statistical significance denoted as: *p<.05, **p<.01 and ***p<.001.

Application to team handball throwing performance (Study IV)

The throwing performance of the participants was as follows: entry velocity = 3.1±0.5 $m \cdot s^{-1}$; throwing velocity = 22.8±1.9 $m \cdot s^{-1}$; accuracy = 0.32±0.09 m; and number of valid throws = 8.8±3.0. Reach measurements and composite scores for the dominant and non-dominant foot are presented in Table 14. There was no throwing velocity and accuracy trade-off (r =

.062, p = .856). Furthermore, the number of throws did not significantly correlate with either throwing velocity (r = -.267, p=.428) or accuracy (r = .330, p = .322). No significant correlations between throwing velocity and the HSEBT, reaches or composite scores, were observed (Table 12, Figure 8). In contrast, HSEBT composite scores and mean radial error were significantly correlated for the dominant foot (CS_{dom} r = .622, p<.05) and approached significance for the non-dominant foot ($CS_{non\text{-}dom}$ r = .584, p=.059), with extension movement pattern composite scores being significant for both the dominant foot (CS_{dom_ext} r = .756, p<.05) and non-dominant foot ($CS_{non\text{-}dom\_ext}$ r = .656, p<.05) (Table 12). Specific reaches – both the L135 (r = .725, p<.05) and R135 (r = .698, p<.05) reaches on the dominant foot and the R135 reach (r = .839, p<.05) on the non-dominant foot – were significantly correlated with the mean radial throwing error. These significant findings corresponded with coefficients of determination ranging from .34 to .70 (Figure 9).

Table 12. *Correlations HSEBT measurements and throwing performance*

Measurement		Measurement (mean±SD)	Throwing velocity	Mean radial error
Dominant	R45 (cm)	79.8±5.9	.395 (p=.230)	.222 (p=.513)
	L45 (cm)	68.2±6.2	.253 (p=.452)	.552 (p=.078)*
	L135 (cm)	87.4±5.6	.177 (p=.602)	.666 (p=.025)**
	R135 (cm)	63.4±11.8	.309 (p=.356)	.553 (p=.078)*
	RROT (°)	122.9±7.0	-.214 (p=.527)	.319 (p=.340)
	LROT (°)	121.3±12.0	-.530 (p=.093)*	.341 (p=.305)
	CS (cm)	297.8±24.1	.382 (p=.246)	.596 (p=.053)*
	CS_{flex} (cm)	148.0±11.2	.349 (p=.349)	.421 (p=.197)
	CS_{ext} (cm)	150.7±17.4	.285 (p=.396)	.631 (p=.037)**
Non-dominant	R45 (cm)	68.5±6.6	-.003 (p=.992)	.350 (p=.291)
	L45 (cm)	80.7±4.6	.211 (p=.533)	.171 (p=.616)
	L135 (cm)	61.1±11.4	.135 (p=.693)	.510 (p=.109)
	R135 (cm)	87.0±6.1	.011 (p=.973)	.812 (p=.002)**
	RROT (°)	114.1±10.3	-.110 (p=.747)	.149 (p=.663)
	LROT (°)	125.2±10.1	-.349 (p=.293)	.452 (p=.163)
	CS (cm)	297.8±24.1	.079 (p=818)	.599 (p=.051)*
	CS_{flex} (cm)	149.2±10.2	.093 (p=.785)	.303 (p=.365)
	CS_{ext} (cm)	148.1±17.4	.099 (p=.772)	.665 (p=.026)**

Note: R45 = Right anterolateral (45°) reach; R135 = Right posterolateral (135°) reach; L135 = Left posterolateral (135°) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach. Statistical significance denoted as: *p<.10, **p<.05.

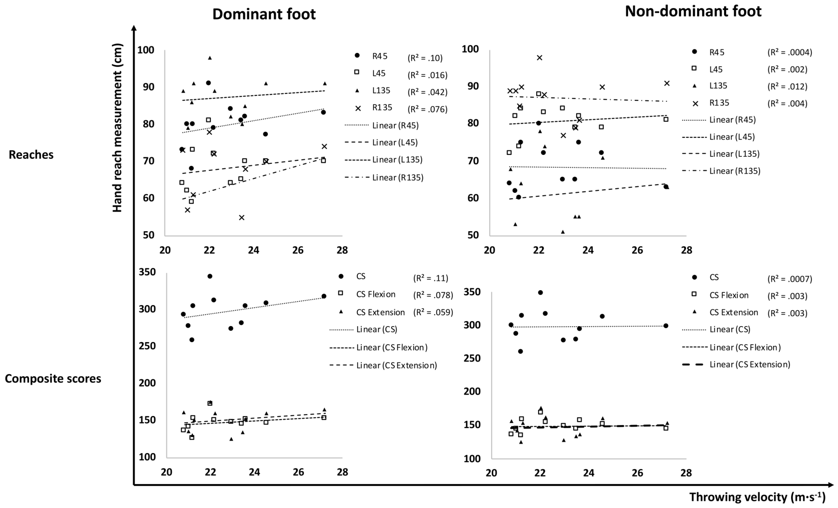

Figure 8. The relationship between hand reach measurements and throwing velocity. *Coefficients of determination (R^2) presented for dominant and non-dominant foot (columns) for both reaches and composite scores (rows).*

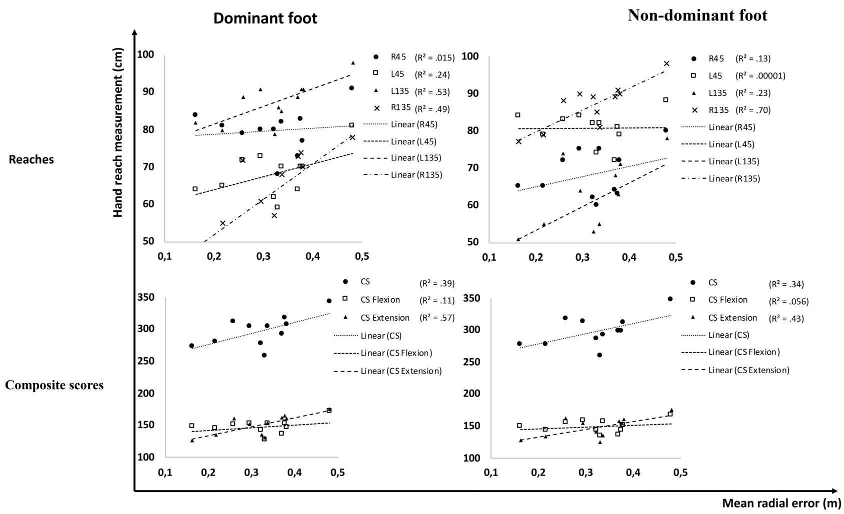

Figure 9. The relationship between hand reach measurements and mean radial error. *Coefficients of determination (R^2) presented for dominant and non-dominant foot (columns) for both reaches and composite scores (rows).*

Discussion

This thesis established the HSEBT as a new test of dynamic postural control that imposes three-dimensional joint mobility demands on the lower extremity, trunk and shoulder joints. The HSEBT is a valid test with moderate to high reliability that requires reach-specific normalization to wingspan. Moreover, the reach-specific influences of age, sex, and level of physical activity have to be accounted for when performing individual or group comparisons. The impact of HSEBT on athletic performance in overhead team handball throwing could not be established, as increased reach measurements were not beneficial to performance in an elite female population.

Content validity

The HSEBT imposes reach-specific joint mobility demands that require simultaneous three-dimensional joint movement contributions from lower extremity, trunk and shoulder joints (Table 5). In comparison to the SEBT the number and magnitude of joint movements (degrees of freedom) are greater. In fact, in 18 out of 22 joint movement comparisons the $\theta_{maxHSEBT}$ were significantly greater than $\theta_{maxSEBT}$. Furthermore, comparisons of $\theta_{maxHSEBT}$ with $\theta_{maxSEBT}$ reported elsewhere support this observation (Aminaka & Gribble, 2008; Doherty et al., 2015; Fullam et al., 2014; Hoch et al., 2011; Kang et al., 2015; Robinson & Gribble, 2008). The greater $\theta_{maxHSEBT}$ may be due to a larger BOS. This notion is supported by other tests with large BOS (i.e. deep overhead squat), which elicit greater hip and knee flexion and comparable ankle dorsiflexion values to $\theta_{maxHSEBT}$ (Butler et al., 2010). Also, the WBLT, which has a large BOS, elicits greater ankle dorsiflexion than both the HSEBT and SEBT (Bennell et al., 1998). However, the influence of the BOS is task dependent, as a greater BOS by itself will not impose greater joint mobility demands. Both the FRT and the deep overhead squat have a similar BOS as both are performed from a bilateral standing position, but the joint mobility demands are different.

If the purpose is to assess lower extremity flexion joint movements, the deep overhead squat and the WBLT are good alternatives. However, many functional and athletic tasks not only require lower extremity flexion, but also flexion in combination with frontal and transverse plane joint movements. In fact, one reason for the three different anterior reaches was to potentially quantify the influence of transverse and frontal plane joint movements on a predominantly sagittal plane flexion task (anterior reach). The pure plane reach (A0) primarily targets sagittal plane joint movements, while the diagonal reaches L45 and R45 combine lower extremity flexion with frontal and transverse plane joint movements (Table 5). Thus, the difference in observed reach measurements can quantify the influence of frontal and transverse plane joint movements on lower extremity flexion movements. Specifically, a lower dorsiflexion was observed in combination with ankle inversion and adduction (L45) than with eversion and abduction (R45) (Table 5). These findings are supported by the work of Tiberio and co-workers who showed that a pronated foot yielded greater dorsiflexion (Tiberio, Bohannon, & Zito, 1989). This might be important as dorsiflexion has been reported to influence other parts of the kinetic chain in the squat movement (Basnett et al., 2013; Fuglsang, Telling, & Sorensen, 2017; Gabriner, Houston, Kirby, & Hoch, 2015; Hoch et al., 2011). In addition, hip joint movement combinations could also impact the observed reach measurement differences, since a lower hip flexion in the L45 (98.8±8.2°) than the R45 reach (108.2±7.9°) was observed. If the hip had the capacity to compensate for the decreased dorsiflexion (L45), an increased hip flexion would be expected in order to increase the reach measurement. Thus, it may be that the other observed hip joint movements (internal rotation and adduction) limit hip flexion, and that the joint is approaching positions of bony impingement (Bowman, Fox, & Sekiya, 2010). In contrast, the observation of hip external rotation in combination with abduction allows greater hip flexion since there is a lower chance of bony impingement (Bowman et al., 2010). Furthermore, $\theta_{maxHSEBT}$ for trunk flexion was observed in the A0 reach, whereas the frontal and transverse plane trunk movements were less than 50% of the observed $\theta_{maxHSEBT}$ in the L45 and R45 reaches (Table 5 and 6). This suggests that neither trunk lateral flexion nor rotation impact reach measurements significantly, and that the difference in reach measurements is due to lower extremity frontal and transverse plane joint movement influences.

How the anterior reaches can be analysed and compared is summarized in Figure 10. Specifically, the anterior reach areas and composite scores can be compared left to right. Also, the A0 reaches can be compared left to right (column in the middle of Figure 10), which allows for similar (=) joint movement comparisons, as the same joint movements are observed at the maximum reach position. As for the L45 and R45 reaches, the sagittal plane joint movements are the same (=), but the frontal and transverse plane joint movements are different (≠), which in turn impact (increase (↑) or decrease (↓)) the sagittal plane joint movements. Comparisons between these tests allow for a comparison of how frontal and transverse plane joint movements influence reach measurements. Then, left to right comparisons can be done to determine differences between the left and right lower extremities. Furthermore, a similar analysis can be applied to the posterior reaches (L135, P180 and R135) to determine the influence of frontal and transverse plane joint movements on extension movement patterns. Overall, the observed differences between the L45 and R45 reach measurements indicate that unilateral testing beyond the sagittal assessment offered by the deep overhead squat should be done, especially since diagonal reaches represent joint movement combinations important to athletic performance such as the tennis forehand and backhand or the ice-hockey shot.

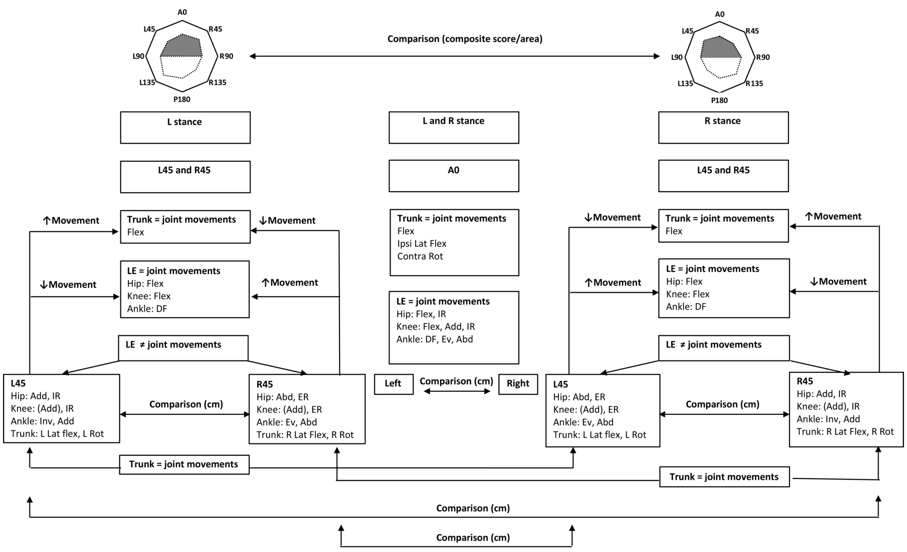

Figure 10. Flowchart for between- and within-limb reach comparisons for the HSEBT. *Analysis of L45 and R45 reaches and how their differences (≠) affect their common joint movements (=). Joint movement abbreviations are presented with Table 5.*

Existing tests tend to target the joint mobility demands of either the lower extremities or the trunk and the upper extremities. Lower extremity joint mobility demands are imposed by the SEBT, YBT, deep squat, in-line lunge and WBLT, hopping and landing tests, whereas the other reach tests, the one arm hop test and the SFMA impose demands on the trunk and/or upper extremities. The demands imposed by the SEBT and YBT have been described previously, whereas hopping tests impose the greatest demand on dorsiflexion (Augustsson et al., 2006). The UQYBT has been described as maximally challenging the mobility and stability of the shoulder and upper trunk (Gorman, Butler, Plisky, et al., 2012); however, no studies have explored these claims. Furthermore, different tests of the SFMA impose trunk and hip mobility demands. Even if the criteria and category scoring of the SFMA have not been validated against motion capture data, comparable tests have been found to elicit joint mobility demands similar to $\theta_{maxHSEBT}$ (Alqhtani et al., 2015; Esola et al., 1996; Leardini et al., 2011). The only other test beside the HSEBT that targets multiple lower extremity, trunk and shoulder joint mobility demands is the deep overhead squat, which is mostly a sagittal plane flexion assessment. Thus, the simultaneous joint mobility demands imposed on the lower extremity, trunk and shoulder joint that target three-dimensional joint movements make the HSEBT unique.

How the joint movements elicited by the HSEBT ($\theta_{maxHSEBT}$) compare with normative ROM values provides an indication of the magnitude of the joint movements elicited by the HSEBT. The $\theta_{maxHSEBT}$ were more consistently within the ranges of normative ROM values (8 out of 22 joint movements) than the $\theta_{maxSEBT}$ (3 out of 18 joint movements). Expecting 22 out of 22 joint movements is unreasonable as the HSEBT testing procedures impose biomechanical constraints (Figure 1), as do functional and athletic tasks, which will not allow for all joint movements to be elicited within normative ROM values (i.e. ankle plantar flexion and knee flexion). Considering that the magnitudes of joint movements elicited by the HSEBT reach measurements are greater than those of the SEBT, it is a better test of functional mobility that should be used to complement traditional ROM tests.

Criterion related validity

There were good to excellent correlations between Max_m and Max_{kin} measurements, similar standard deviations, and a shared variance ranging from 63 to 98% for all HSEBT tests. Of the 20 comparisons, 12 tests had a shared variance ≥ 90% (Table 7). However, these values are lower than the 98% shared variance reported for the SEBT reaches (Bastien et al., 2014a). Fixed biases were observed for all tests in a manner that appears to be reach-specific. Fixed biases in flexion, lateral and extension movement patterns ranged from 2.2 to 5.1 cm, 3.8 to

12.8 cm and 9.7 to 12.8 cm respectively (Table 7). These biases are greater than 90% of all SEBT reaches, which are reported to have a difference of less than 2.32 cm (Bastien et al., 2014a).

The lower criterion validity observed for the HSEBT than the SEBT can be partially explained by the kinematic methods used to calculate the Max_{kin}. First, the 5th metacarpal marker was used to represent the position of the distal point of the third digit, which underestimates the visual measurement. Second, the center of the foot coordinate system was located posterior to the center of the testing mat. Based on the location of the stance foot coordinate system, and assuming a similar horizontal orientation of the hand segment in the global coordinate system, the greater biases observed in extension than flexion movement patterns were expected (Table 7). Differences in hand orientation in the global coordinate system may explain the observed differences in the lateral reach measurements. Directional specific differences in fixed biases were observed in ipsilateral and contralateral overhead reaches of 3.8 to 5.1cm and 12.0 to 12.8cm, respectively. The ipsilateral hand had a more vertical orientation in the maximum reach position in the ipsilateral than in the contralateral overhead reach (visual observation). Thus, the 5th metacarpal marker will better approximate the position of the most distal point of the third digit in the ipsilateral reach in the Y-direction of the global coordinate system of the laboratory.

Calculation of Max_{kin} for the rotational reaches was based on the orientation of the ipsilateral arm resolved in the coordinate system of the stance foot. Specifically, the Max_{kin} measurements were higher and lower than Max_m for contralateral and ipsilateral rotational reaches respectively (Table 7). A greater contribution of shoulder horizontal adduction in contralateral than horizontal abduction in ipsilateral rotational reaches (visual observation) can explain these observed differences. Overall, based on the good to excellent correlation coefficients between Max_m and Max_{kin}, and on the fact that the kinematic methods used can explain the observed fixed biases, manual measurements of hand reach distance (cm) and rotation (°) seem to be valid.

Construct validity

Large ranges of shared variance between HSEBT and SEBT area and composite scores (5.2 to 67.7%) and reach specific correlations (r = -.182 to .822) were observed. These findings indicate that HSEBT reaches measure both similar and different aspects of dynamic postural control than their SEBT counterparts, with the anterior reaches having the highest correlations. The strength of the shared movement synergies could explain some of the reach-specific observed differences. Specifically, the lateral reach with a weak movement synergy (4/12) had little to no correlation, while the lateral reach with a strong movement synergy (9/12) had fair to moderate correlation (Table 5). Furthermore, posterior reaches had moderate shared movement synergies (6-8/12) and fair correlations, while rotational and anterior reaches with moderate to strong shared movement synergies (8-10/12) had fair to good correlations (Table 5). Since the anterior HSEBT (A0, R45 and L45) and the posterior SEBT (P180, L135 and R135) reaches also had strong shared movement synergies (8-11/12, obtained from Table 5) with joint movements of a similar magnitude, especially the hip joint (Table 5), an anterior HSEBT to posterior SEBT CS comparison should not influence the moderate to good anterior CS correlations. However, correlation coefficients mostly decreased for these comparisons (Table 8). Thus, it appears that a shared movement synergy is only one of the plausible explanations for the variable correlations between HSEBT and SEBT reaches. It might be that rather than an overall synergy, one specific joint movement of a shared movement synergy (i.e. dorsiflexion) has a greater influence on outcome measurements than other joint movements. In fact, dorsiflexion has been found to predict SEBT reach performance (Basnett et al., 2013; Gabriner et al., 2015; Hoch et al., 2011). However, the influence of specific joint movements (i.e. dorsiflexion) on HSEBT reach measurements has not been explored. Another reason for the differences in the correlations between anterior and posterior reaches may lie in the similarity of LOS. It is likely that the COP will move in the same direction as the reach for both the HSEBT and the SEBT, which could explain why the anterior HSEBT and SEBT CS comparison had a stronger correlation than the anterior HSEBT and posterior SEBT CS comparison (Table 8). Future studies should explore how the COP behaves and possibly influences different HSEBT reach measurements. In addition, visual feedback could have influenced the anterior to posterior SEBT and HSEBT comparisons, since visual feedback of the reaching target is available for the anterior, but not for the posterior reaches. In summary, the current findings indicate that the HSEBT measures different aspects of dynamic postural control than the SEBT, especially in the lateral, posterior and rotational reaches.

Test-retest reliability

High to moderate ICC values (range = 0.80 to 0.96) were observed for all HSEBT reaches except right foot R90 reach (0.77). These ICC values are comparable or better to those reported for other tests of dynamic postural control (see Appendix I-III for details). Specifically, test-retest ICC values for the comparable dynamic postural control reach tests range as follows: SEBT (0.62 to 0.92) (Kinzey & Armstrong, 1998; Lopez-Plaza, Juan-Recio, Barbado, Ruiz-Perez, & Vera-Garcia, 2018; Munro & Herrington, 2010), YBT (0.51 to 0.98) (Calatayud, Borreani, Colado, Martin, & Flandez, 2014; Clark et al., 2010; Faigenbaum et al., 2014; Freund et al., 2018; Kenny et al., 2018; Plisky et al., 2006; Shaffer et al., 2013), SRT (0.78 to 0.99) (Field-Fote & Ray, 2010; Katz-Leurer et al., 2009; Radtka et al., 2017), FR, lateral and multidirectional reach (0.92 to 0.99) (Brauer et al., 1999; Duncan et al., 1990; Newton, 2001), CKCUEST (0.90 to 0.96) (Goldbeck & Davies, 2000; Tucci, Martins, Sposito Gde, Camarini, & de Oliveira, 2014) and the UQYBT (0.80 to 0.99) (Gorman, Butler, Plisky, et al., 2012; Westrick, Miller, Carow, & Gerber, 2012) .

Response stability, as quantified by SEM, ranged from 0.3 to 2.8 cm and 1.7 to 2.6°, which is comparable to that reported for other dynamic postural control reach tests on the same scale (cm). Specifically, reported SEM values range as follows: SEBT (3.4 to 4.0 cm) (Kinzey & Armstrong, 1998), YBT (1.7 to 5.4 cm) (Freund et al., 2018; Kenny et al., 2018; Shaffer et al., 2013), FR (2.1 to 2.4 cm) (Lin, Chen, Tang, & Wang, 2012), SRT (2.0 to 4.0 cm) (Radtka et al., 2017) and UQYBT (composite score = 2.2 to 2.9 cm) (Gorman, Butler, Rauh, et al., 2012). The observed CV values (2.1 to 13.1%) are at least comparable to if not greater than those observed for the SEBT (3.6 to 4.4%) (Plisky et al., 2006), which is the only study to report CV values for the reach and functional mobility tests (Appendix I and IV). Coefficient of variation values for test-retest reliability for other dynamic postural control tests are mostly greater (Appendix II and III). Thus, the reported HSEBT CV values (range = 2.1 to 13.1%) appear to be better than or comparable to established tests of dynamic postural control.

Inter-rater reliability

The inter-rater reliability for the HSEBT was high for all reaches, with ICC values ranging from 0.90 to 0.98 (Table 9), which is comparable to or better than those reported for other reach tests, SEBT (range = 0.81 to 0.94) (Gribble, Kelly, Refshauge, & Hiller, 2013; Hertel et al., 2000; Hyong & Kim, 2014), YBT (0.80 to 1.00) (Almeida et al., 2017; Clark et al., 2010; Faigenbaum et al., 2014; Freund et al., 2018; Plisky et al., 2009; van Lieshout et al., 2016) and FR (0.73 to 0.92) (Lin et al., 2012). Despite the high ICC values, the MANOVA results suggest that in 5 of the 20 tests at least one rater differed systematically from the other raters. Even if these differences were lower than the MDC values, the effect of the test administrator on the results cannot be ruled out.

The observed SEM values ranged from 0.3 to 2.1 cm and 1.8 to 2.4°, which is comparable to those reported for other dynamic postural control reach tests such at the YBT (0.7 to 3.3 cm) (Plisky et al., 2009), SEBT (2.3 to 3.9 cm) (Hertel et al., 2000) and FR (2.1 to 2.3 cm) (Lin et al., 2012). Since no other reach tests to date are measured in degrees, comparisons of SEM values with other studies are not possible. Furthermore, comparisons of reported CV values (3.1 to 14.6%) to other reach, functional mobility, hopping and landing tests cannot be made since, to the author´s knowledge, these values have not been established (Appendix I-IV). However, as inter-rater reliability was calculated from different sessions, comparisons with CV values from test-retest analyses can be made. As described previously, these values are mostly greater (Appendix II and III).

Both differences and ranges in CV values followed a similar pattern for both test-retest and inter-rater reliability. One potential reason for these relatively large variations is the influence of visual feedback. When subjects could see how far they reached (anterior reaches) a considerably lower variation was observed (range test-retest CV = 2.1 to 3.8%; range inter-rater CV = 3.1 to 5.2%), than when the subjects could not see (lateral and posterior) (range test-retest CV = 5.2 to 13.1%; range interrater CV = 5.6 to 14.6%).

Calculations of MDC values were carried out as they are important from both a clinical and research perspective (Haley & Fragala-Pinkham, 2006). Based on MDC calculations and personal clinical experience, a change or difference score of 5 cm in anterior and 7 cm in lateral and posterior reach measurements constitutes a true difference or change in outcome measurements. These values are comparable to some of the lower MDC values reported for the SEBT (5-7cm; 6-8% of leg length) (Freund et al., 2018; Hyong & Kim, 2014; Kenny et al., 2018; Munro & Herrington, 2010; Shaffer et al., 2013; van Lieshout et al., 2016) (Appendix I).

In summary, the HSEBT has equal or better reliability in comparison with other tests of dynamic postural control and functional mobility. The established CV and MDC values allow for interpretation of change and difference scores for within- or between-subject comparisons.

Factors influencing HSEBT

Anthropometry

Anthropometric measures were found to have reach-specific influences. As expected, an influence of anthropometry was observed in anterior reaches as wingspan explained 11.7 and 34.6% of the variation in L45 and R45 reach measurements respectively. These findings were greater than the observed CV values (range = 3.0 to 5.2%). In addition, between-group comparisons (age, sex and level of physical activity) using normalized anterior reaches (% of wingspan) resulted in a change from non-significant to significant differences with effect sizes changing from trivial and small (range *d* = .01 to .28) to medium (range *d* = .50 to .72) (Table 10). However, posterior reaches were unexpectedly only influenced by leg length (L135), and only explained a lower portion of the variance than the observed CV values (5.2 to 6.6%, see Table 9). Also, leg length had a non-significant contribution to the R45 reach measurement (Appendix IX). As expected, no anthropometric measures influenced the rotational reaches. Overall, these findings suggest a reach-specific normalization of the anterior reaches (L45 and R45) to wingspan.

Reach-specific normalization procedures, as suggested for the HSEBT, are not used for other reach tests. Even if six of eight SEBT foot reaches were significantly correlated with leg length (range R^2 = .02 to .23) (Gribble & Hertel, 2003) a general normalization was recommended and has since been widely used (Gribble et al., 2012). The other hand reaches, UQYBT, forward, lateral and posterior reaches, have all been normalized to arm length even if the influence on reach measurements has not been demonstrated.

Specifically, forward and lateral reach outcome measurements are difference scores from the starting position (arm flexed or abducted to 90 degrees) to the maximum reach position, and thereby normalized to arm length. The UQYBT measurements are commonly normalized to arm length (Borms, Maenhout, & Cools, 2016; Butler et al., 2014; Gorman, Butler, Plisky, et al., 2012; Taylor, Wright, Smoliga, Depew, & Hegedus, 2016; Westrick et al., 2012), but the influence of arm length on reach measurements has yet to be explored.

Age

There are reach-specific effects of age. Specifically, the young group had greater measurements with medium effects observed for the R135 and the normalized L45 and R45 reaches. The observed group difference for the R135 reach (7.6 cm) (Table 10) was within the range of MDC values (5.5 to 7.9 cm) (Table 9). Based on the age groups being significantly different ($p<0.05$); a medium effect size (*d*= .55); MDC values being calculated for a conservative confidence interval (95%) (Haley & Fragala-Pinkham, 2006); and the previously recommended difference score of 7 cm, age was interpreted to influence the R135 reach measurement. The combination of these comparisons is a more robust interpretation of findings, since it is not based solely on significance testing. Thus, age should be considered when performing between-individual or group comparisons for the R135 and normalized L45 and R45 reach measurements. However, these findings may be influenced by the young group consisting of athletes, while the older group consisted of both athletes and recreationally active participants (see section below).

A similar influence of age has been reported using different reach tests. In a young population, SEBT measurements increase with age (Gonzalo-Skok et al., 2017; Holden et al., 2016; McCann et al., 2017). Specifically, older individuals (15.6±0.6 years) had increased SEBT measurements in some directions when compared to younger basketball players (13.7±0.5 years) (Gonzalo-Skok et al., 2017). McCann and co-workers also reported that older football players (19.8±1.4 years) had greater SEBT reach measurements than younger players (15.9±1.1 years) (McCann et al., 2017). In an older population (28.7±6.3 years) younger participants (<30 years of age) had greater reach measurements than older participants (Teyhen et al., 2014), and in an older female population (50 to 79 years of age) a decrease with age was observed (Freund et al., 2018). However, only one study reported effect sizes (Gonzalo-Skok et al., 2017), and none of these studies compared group differences to MDC values (Munro & Herrington, 2010), which could change the interpretation of some of the results. Age has also been reported to influence arm reach tests such as the UQYBT. Teyhen and co-workers reported no influence of age (Teyhen et al., 2014), while Borms and Cools reported that increased age decreased reach measurements in female volleyball, but not tennis and team handball players (Borms & Cools, 2018). However, when compared to MDC values (Gorman, Butler, Rauh, et al., 2012), only the superolateral reach direction decreased with age (Borms & Cools, 2018). Moreover, younger participants have been reported to have significantly greater dorsiflexion (WBLT) ROM (2.9°) (Teyhen et al., 2014). Again, the group difference is lower than the established MDC values (4.5 to 4.7°) (Powden et al., 2015). Overall, the increased HSEBT reach measurements in a younger population for selected reaches agree with what has been reported for other reach tests in a similar age group.

Level of physical activity

Athletes were found to have significantly greater reach measurements than the recreationally active participants for the R135 and the normalized L45 and R45 reaches. The significant between-group differences, the medium effect sizes and the group difference for the R135 reach being greater than MDC values justify the inference that level of physical activity increases L45, R45 and R135 reach measurements. However, the interpretation should be done cautiously as these findings coincide with the significant reaches for the age group comparisons where the athletic population was significantly younger than the recreationally active (large effect). Also, level of physical activity explained 3.3 and 6.5% of the L135 and R135 reach measurements respectively, but these values were lower than the observed CV values for these reaches (Table 9). However, it appears that level of physical activity should be considered when performing between-individual or group comparisons using the HSEBT.

The level of physical activity has been found to influence reach measurements in comparable tests such as the SEBT (Ambegaonkar et al., 2013; Bressel et al., 2007; Sabin et al., 2010; Thorpe & Ebersole, 2008). Both female dancers and soccer players seem to have greater SEBT reach measurements in comparison to their recreationally active counterparts

(Ambegaonkar et al., 2013; Thorpe & Ebersole, 2008). In contrast, Sabin and co-workers found that active controls had greater SEBT reach measurements than basketball players (Sabin et al., 2010). Furthermore, there are sport-specific SEBT reach differences e.g. soccer players had greater SEBT reach measurements than basketball players, but there was no observed difference between gymnasts and soccer players (Bressel et al., 2007). However, the aforementioned studies neither reported effect sizes nor compared group differences to MDC values. Thus, it seems that level of physical activity and type of sport influence dynamic postural control as measured by the SEBT.

An equivocal influence of level of physical activity has been reported for the UQYBT (Borms & Cools, 2018; Bullock, Brookreson, Knab, & Butler, 2017; Myers, Poletti, & Butler, 2017; Taylor et al., 2016). Wrestlers had greater reach measurements than baseball players (high school level) (Myers et al., 2017), while baseball players had greater normalized hand reach measures than athletes participating in basketball, lacrosse, track and field and cross-country (large effect sizes) (Taylor et al., 2016). However, no pairwise comparisons between the other sports were performed (Taylor et al., 2016). Furthermore, team handball players had significantly greater medial reach measurements than volleyball players (Borms & Cools, 2018), while swimmers at collegiate competition level had significantly greater normalized reach measurements than those at a lower level (high school) (Bullock et al., 2017). Effect sizes were reported in one study (Taylor et al., 2016) and comparisons to MDC values were only possible in one other study (Borms & Cools, 2018) since reported MDC values were not normalized (Gorman, Butler, Rauh, et al., 2012). This would change the interpretation to a non-significant difference between team-handball and volleyball players (Borms & Cools, 2018). Overall, it appears that the influence of level of physical activity on HSEBT reach measurements is in agreement with what has been reported for both the SEBT and the UQYBT.

Influence of sex

Females had significantly greater normalized L45 and R45 reach measurements with a medium effect size. These findings could be influenced by the female group being younger than the male group (d = 0.83) since younger participants have greater normalized L45 and R45 reach measurements. It is interesting to note that males have significantly greater absolute R45 reach measurements with a small effect size and a group difference less than MDC values. Normalization to wingspan changes this relationship completely with females having greater measurements (*d* = 0.64). These findings might be due to males having a greater wingspan (10.9 cm; *d* = 1.51), and the fact that the R45 reach is where wingspan accounts for the greatest variation of the measurement (34.6%). Thus, females are better able to combine different joint movements to maximize R45 reach measurements despite having unfavourable anthropometrics. In addition, sex had a medium effect and explained 4.2 and 8.9% of the variance of the R45 and L45 reach measurements, greater than most CV´s for R45 and L45 reaches (3.0 to 5.2%). However, sex was found to have a non-significant contribution in the validation model of the regression analysis.

Similar to our findings, physically active females have been found to have greater SEBT reach measurements than their male counterparts (Gribble et al., 2009). However, in an earlier study, Gribble and co-workers reported no influence of sex on normalized SEBT reach measurements (Gribble & Hertel, 2003). In contrast, others have found males (Sabin et al., 2010) and athletic males (Gorman, Butler, Rauh, et al., 2012) to have greater SEBT reach measurements than their female counterparts. In the aforementioned studies effect sizes were not reported and group differences were not compared to MDC values.

Contrary to our findings, males have been reported to have greater UQYBT reach measurements. No difference in reach measurements were reported in recreationally active males and females (Gorman, Butler, Plisky, et al., 2012), but male volleyball, tennis and team handball players have been reported to have significantly greater hand reach measurements than their female counterparts (Borms & Cools, 2018). In swimming, male athletes have greater reach measurements than their female counterparts, with effect sizes ranging from medium to large (Butler et al., 2014). Male active duty service members on average had a 4.6% greater reach measurement than their female counterparts in different age groups (Teyhen et al., 2014). The greater reach measurements observed for males may be due to greater strength demands as the UQYBT is performed from a three-point plank position (Westrick et al., 2012).

Influence on performance – throwing velocity

In study IV throwing velocity and accuracy was analyzed separately, as neither a trade-off nor a correlation between throwing velocity and throwing accuracy were observed. These findings agree with previous observations (Garcia, Sabido, Barbado, & Moreno, 2013; van den Tillaar & Ettema, 2003, 2006). The throwing velocities observed are comparable to those reported elsewhere for elite female handball players (Granados, Izquierdo, Ibanez, Bonnabau, & Gorostiaga, 2007; Granados, Izquierdo, Ibanez, Ruesta, & Gorostiaga, 2008; Vila et al., 2012). Individual HSEBT reach measurements and composite scores did not correlate with throwing velocity. Hip extension, pelvic rotation, trunk rotation and extension are joint movements associated, on the one hand, with the approach, cocking and acceleration phase of the throw (van den Tillaar & Ettema, 2007; Wagner et al., 2011), and on the other hand, with the different posterior reaches (Eriksrud, Federolf, Anderson, & Cabri, 2018). Furthermore, Wagner and co-workers found that maximum trunk and pelvic rotation during the throw were correlated with throwing velocity (Wagner et al., 2011). Therefore, it seemed plausible to expect a correlation between HSEBT results and throwing velocity, especially considering that limiting proximal mobility (trunk and shoulder complex) by bracing decreased throwing velocity (Roach & Lieberman, 2014). Our findings, however, did not support this hypothesis. Considering that all subjects were elite level handball players, they could all have had sufficient joint mobility to generate high throwing velocities (ceiling effect). In fact, comparisons of L135 and R135 reach measurements (Table 12) with reference data from study II (Table 9) showed that the handball players had reach measurements greater than the recommended difference score (7 cm). However, when compared to the athlete group from study IV (Table 10) no such difference could be observed. Furthermore, no differences could be observed for flexion and rotational movement patterns. These comparisons may indicate that the players studied had sufficient functional mobility and dynamic postural control associated with the cocking and acceleration phase for the generation of high throwing velocities.

Based on current and previous findings, it appears that ROM (Schwesig et al., 2016; van den Tillaar, 2016), functional mobility and dynamic postural control measurements (Bullock et al., 2018) do not predict throwing velocity. Thus, mobility and dynamic postural control measurements should perhaps be analyzed in combination with measures of other neuromuscular qualities to better understand the underlying factors influencing throwing velocity. Muscular strength and power have been more studied and found to be significantly correlated with throwing velocity (Chelly, Hermassi, & Shephard, 2010; Cherif, Chtourou, Souissi, Aouidet, & Chamari, 2016; Debanne & Laffaye, 2011; Fleck et al., 1992; Gorostiaga, Granados, Ibanez, & Izquierdo, 2005; Granados et al., 2007; Manchado, Tortosa-Martinez, Vila, Ferragut, & Platen, 2013; Marques, van den Tilaar, Vescovi, & Gonzalez-Badillo, 2007). Specifically, power tests (kneeling medicine ball throw) and strength and power training (overhead medicine ball throwing) that target joint movements similar to those observed in the posterior overhead reaches (shoulder flexion, hip and trunk extension) have been found to be correlated with throwing velocity (Debanne & Laffaye, 2011; Hermassi, van den Tillaar, Khlifa, Chelly, & Chamari, 2015). Thus, combining these tests with the HSEBT posterior reaches might be a good multifactorial model of neuromuscular qualities to explain throwing velocity.

Influence on performance – throwing accuracy

The throwing accuracy observed in the current study (mean radial error: 0.32±0.09 m) was comparable with previous findings (van den Tillaar & Ettema, 2003, 2006; Wagner, Buchecker, von Duvillard, & Muller, 2010; Wagner et al., 2011; Zapartidis, Gouvali, Bayios, & Boudolos, 2007). Unlike throwing velocity, accuracy has not received the same attention in the literature. The effect of instructions (Garcia et al., 2013; van den Tillaar & Ettema, 2003, 2006), age and sex (Gromeier, Koester, & Schack, 2017), fatigue (Nuno et al., 2016; Zapartidis et al., 2007), performance level (Rousanoglou, Noutsos, Bayios, & Boudolos, 2015; van den Tillaar & Ettema, 2006), temporal constraints (Rousanoglou et al., 2015), throwing techniques (Wagner et al., 2010) and laterality (van den Tillaar & Ettema, 2009) on throwing accuracy have been explored. However, only two studies have explored the influence of neuromuscular qualities, strength and power on accuracy, with non-significant findings (Raeder, Fernandez-Fernandez, & Ferrauti, 2015; Zapartidis et al., 2007). No studies so far have explored the influence of functional mobility or dynamic postural control on accuracy. Furthermore, accuracy has been little studied in other comparable overhead and throwing sports. In baseball, static stretching did not influence accuracy (Haag, Wright, Gillette, & Greany, 2010), while better static balance in baseball (Marsh, Richard, Williams, & Lynch,

2004) and lacrosse (Marsh, Richard, Verre, & Myers, 2010) improved accuracy (Marsh et al., 2010).

Considering the limited information available on the influence of dynamic postural control and functional mobility on throwing accuracy, our findings provide valuable information on this important throwing performance factor. We showed that greater posterior overhead hand reach measurements are correlated with lower throwing accuracy. One speculative interpretation of this finding might be that posterior overhead reaches quantify the proprioceptive and balance demands associated with throwing. Measures of proprioception are correlated with successful basketball free-throw performance (Sevrez & Bourdin, 2015), but not throwing accuracy in baseball (Freeston, Adams, & Rooney, 2015) or lacrosse (Marsh et al., 2010). Based on their findings, Freeston et al. (2015), argued that proprioception of the entire kinetic chain should be assessed since proprioception of the shoulder joint in isolation did not correlate with throwing accuracy. If proprioception is measured by the HSEBT and more accurate throwers have better proprioception, then lower posterior overhead reach measurements represent better, or a better use of, proprioceptive information. It may be that some players stopped at a safer margin to LOS based on proprioceptive input that resulted in a lower reach measurement.

Perspectives and implications for future research

The influence of COP measures (i.e. velocity and excursion) and COM movements (i.e. vertical) on HSEBT reach measurements should be explored as they have been reported to influence SEBT reach measurements (Bastien et al., 2014b; Pionnier et al., 2016). Also, time to maximum reach position, trajectory of reaching hand(s) and deviation from reaching direction and target could provide additional information about dynamic postural control. In fact, these measures have been explored for the SEBT and reported to be different in patients with chronic ankle instability (Pionnier et al., 2016).

The HSEBT consists of 20 different hand reaches, which may provide redundant reach measurement information. In fact, reach measurements have been used as one argument for the reduction from eight (SEBT) to three (YBT) foot reaches (Hertel et al., 2006). However, reducing the number of reaches based on one discrete measurement (maximum reach) may be too simple, as more information may be contained in the different hand reaches. Specifically, analyzing coordination based on phase angles, angle-angle plots or principle component analysis may provide more insight about the dynamic postural control information expressed by the different hand reaches. This information (i.e. similarities and differences of principal components of different reaches), in combination with reach measurements, may allow for a better analysis of how to reduce the number of hand reaches.

HSEBT hand reaches did not correlate with overhead team handball throwing velocity, but one reach (right foot L135 reach for right handed players) was significantly correlated with tennis serve velocity (Eriksrud, Ghelem, Henrikson, Englund, & Brodin, 2018). The HSEBT reaches tested in this study were selected based on the same principle used for assessing team handball players; eliciting combinations of joint movements similar to those used in the preparation and acceleration phase of the serve (Elliott, 2006; Kovacs & Ellenbecker, 2011; Tubez et al., 2015; Wagner et al., 2014). This particular hand reach elicited dominant arm shoulder flexion, trunk extension, minimal ipsilateral rotation and contralateral lateral flexion (Table 5). Based on these findings, it appears that the combination of dominant shoulder flexion, previously found to be significantly correlated to serve speed (Cohen, Mont, Campbell, Vogelstein, & Loewy, 1994), with trunk extension and ipsilateral rotation offers the best representation of joint movement combinations, or represents significant boundary conditions associated with the preparation and acceleration phases of the tennis serve. The ability to use the combination of these joint movements of a certain magnitude might allow players to produce greater linear and angular momentum and thereby increase serve speed (Elliott, Marsh, & Blanksby, 1986). This has been corroborated in a study in which elite players with high serve speeds were capable of performing backswings of greater magnitude (Girard, Micallef, & Millet, 2005). It is important to note that the performance level of the participants in this study ranged from regional to international, which supports the ceiling effect discussed in study III. Thus, it may be that the HSEBT can be applied to team handball throwing performance where certain cut-off scores can be established, beyond which throwing performance is not positively influenced.

Even if the HSEBT has a variable relationship to overhead athletic performance as reported for team handball overhead throwing (study IV) and tennis serve performance (Eriksrud, Ghelem, et al., 2018), the HSEBT may find other applications in overhead athletes. For example, in team handball, shoulder pain is highly prevalent (Myklebust, Hasslan, Bahr, & Steffen, 2013), and isolated tests of shoulder mobility have a variable capacity to predict shoulder injuries (Andersson, Bahr, Clarsen, & Myklebust, 2017; Clarsen, Bahr, Andersson, Munk, & Myklebust, 2014). Based on these shortcomings, and the kinetic chain contributions to throwing performance, it has been argued that kinetic chain assessments including the trunk and the lower extremities should be an integral part of routine shoulder assessment (Kibler & Sciascia, 2016; Young et al., 1996). The scapula serves as the dynamic base of the glenohumeral joint to allow for optimal positioning of the glenoid to ensure stability (Kibler & Sciascia, 2016). In fact, the dynamic scapular positioning has a highly coordinated interaction with both the shoulder joint and the thoracic spine (Crosbie et al., 2008). Furthermore, trunk and hip joint movements (Hirashima et al., 2007; Kibler & Sciascia, 2016), muscle activation patterns (Hirashima, Kadota, Sakurai, Kudo, & Ohtsuki, 2002; Kibler, Chandler, Shapiro, & Conuel, 2007; Kibler & Sciascia, 2016) and energy transfers (Happee & Van der Helm, 1995; Hirashima et al., 2007; Hirashima et al., 2008) occur in a proximal to distal sequence to ensure dynamic positioning of the scapula for different upper extremity tasks (Kibler & Sciascia, 2016). Furthermore, Kibler and co-workers also argue that core muscle function should be assessed dynamically in three dimensions and include trunk control over a planted leg (Kibler et al., 2006). Currently there are no standardized tests that address the dynamic hip and trunk movements in this patient population. Thus, the HSEBT may be a good assessment tool to target regional interdependence and move beyond the biomedical model of isolated joint assessments (Wainner et al., 2007) in this patient population.

Hand reaches may also be a valuable assessment tool in other diagnoses, such as low back pain (LBP). Specifically, the lumbo-pelvic rhythm in the sagittal plane, forward bending in bilateral stance, is reported to be altered in patients with LBP (Laird et al., 2014; Laird et al., 2016). This rhythm has also been reported in both lateral trunk bending (frontal plane) (Laird et al., 2016; Tojima et al., 2016) and axial rotation (transverse plane) (Taniguchi, Tateuchi, Ibuki, & Ichihashi, 2017), but was most commonly assessed for patients with LBP in the sagittal plane (Laird et al., 2014). It has been reported that different stance widths and angulations (neutral and externally rotated lower extremities) influence the lumbo-pelvic rhythm in forward bending (Zhou et al., 2016), which indicates a task-specific dynamic postural control of the lumbo-pelvic rhythm influenced by both BOS and lower extremity joint movement contributions. Specifically, hip mobility may influence this rhythm, and hamstrings flexibility have been reported to do so (Zawadka et al., 2018). Thus, hand reaches may be a strategy to explore the lumbo-pelvic rhythm in a uni- and multi-directional manner in patients with LBP.

The anterior reaches can be used to assess different lower extremity functional limitations. Based on hip joint movements elicited by the left foot L45 and right foot R45 hand reaches, it may well be that these reaches can be used as a weight-bearing version of a common clinical test for femoroacetabular impingement, which is currently done in supine with the hip passively brought into flexion, adduction and internal rotation. Previously Kivlan and co-workers designed a similar test, the cross-over reach test, to assess intra-articular hip related pathology (Kivlan et al., 2013). Since a limited description of testing procedures is provided and the support foot is free to counterbalance (Kivlan et al., 2013) the HSEBT might be a better alternative.

Conclusions

In conclusion the current thesis demonstrated that:

1. The HSEBT is a valid and reliable measure of dynamic postural control.
2. The HSEBT measures different aspects of dynamic postural control, especially in the posterior and lateral directions, compared to the SEBT.
3. Greater and more joint movements are elicited by the HSEBT reaches in comparison to the SEBT, making the HSEBT a useful addition to tests of functional mobility.
4. Normalization to wingspan is reach-specific and should only be applied to the L45 and R45 reaches.
5. HSEBT reach measurements L45 and R45 are significantly influenced by age, sex and level of activity, while the R135 reach is significantly influenced by age and level of physical activity.
6. Increased dynamic postural control as measured by the HSEBT was not beneficial to overhead throwing performance in a group of female international level team handball players.

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Paper I

Journal of
Functional Morphology and Kinesiology

MDPI

Article

Reliability and Validity of the Hand Reach Star Excursion Balance Test

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Received: 28 June 2017; Accepted: 1 August 2017; Published: 4 August 2017

Abstract: Measuring dynamic postural control and mobility using task-based full-body movements has been advocated. The star excursion balance test (SEBT) is well-established, but it does not elicit large upper body joint movements. Therefore, the hand reach star excursion balance test (HSEBT) was developed. The purpose of the current study was to assess the inter-rater and test-retest reliability and validity of the HSEBT. Twenty-nine healthy male subjects performed ten HSEBT reaches on each leg on four different occasions, led by three different raters. Reach distances were recorded in centimeters and degrees. Then, twenty-eight different healthy males performed the HSEBT while using a standard motion capture system. Reliability was assessed using the intraclass correlation coefficient (ICC) (range 0.77–0.98). Stability of measurement was assessed using the standard error of measurement (SEM) (range 0.3–2.8 cm and 1.7°–2.6°) and coefficient of variation (CV) (range 2.1–14.6%). Change scores were obtained using minimal detectable change (MDC_{95}) (range 0.9–7.9 cm and 4.7°–7.2°). Observed (Max_m) and calculated (Max_{kin}) maximum hand reach measurements showed good to excellent correlations. Bland Altman analysis established a fixed bias for all tests, which can be partially explained by the kinematic calculations. In conclusion, the HSEBT is a valid and reliable full-body clinical tool for measuring dynamic postural control and functional joint mobility.

Keywords: dynamic postural control; balance; posture; reliability; validity

1. Introduction

A task-based clinical assessment of mobility and dynamic postural control that elicits full kinematic chain (foot to hand) three-dimensional joint movements has been advocated [1,2]. This is clinically important considering that testing of joints in isolation does not capture the neuromuscular control involved in the joint or muscular synergies necessary for dynamic postural control. Foot and hand reaches are task-driven tests that can capture this interaction. The star excursion balance test (SEBT) is a well-established, reliable clinical tool for dynamic postural control [3] that assesses different neuromuscular functions, such as proprioception [4], joint range of motion (ROM) [5] and lower extremity strength and balance [6]. Clinically, the SEBT has proved to be sensitive in detecting functional deficits in patients with different lower extremity dysfunctions and diagnoses [3], improvements in response to training [7], and predicting the risk of lower extremity injuries [8]. However, the SEBT does not examine trunk, upper extremity and all hip joint movements in the assessment of dynamic postural control, and therefore is not well suited to revealing functional deficits in these joints in combination with lower extremity joint movements. A systematic combination of hand reaches has the potential to capture this interaction.

Hand reaches beyond arm's length from standing elicit a dual role of the trunk and lower extremities in both postural stability and joint movements in transferring the hand to the target, linking posture and movement coordination [9–11]. As reach distance increases, the trunk, upper and lower extremities work together as one functional unit to move the body toward the target [9] with a greater movement of center of the mass (COM) [9,11] and increased joint movements [12]. In addition, different reach directions describe different limits of stability [13]. Furthermore, 95% of the activities of daily living involve trunk and arm movement [14], and falls often occur while reaching [15]. Hand action is also closely linked with movement of the rest of the body and thus with performance in volleyball, tennis, golf and throwing sports. Therefore, a systematic combination of hand reaches in different directions might prove to be a highly relevant clinical tool.

Currently, different hand reach tests are used for assessing dynamic postural control and upper body mobility and stability [13,16–19]. However, a validated and reliability-tested hand reach test battery, comparable to the SEBT, that elicits ankle, knee, general hip, trunk and upper extremity joint movements in standing is currently not available. Such a test battery would provide the clinician with a tool for quantitative (cm or °), qualitative (magnitude and coordination) and subjective assessment of dynamic postural control and full body movement (functional mobility). Therefore, we developed the hand reach star excursion balance test (HSEBT), which consists of ten different hand reaches on each foot in the same directions as the SEBT, with the addition of two rotational reaches. The HSEBT measures hand reach distance (cm or °) while engaging the full kinetic chain (hand to foot) under reach-specific constraints dictated, for example, by stance position and reaching arm. Thus, the HSEBT has the potential to complement the SEBT as a clinical tool in the assessment of dynamic postural control.

The current paper reports on two studies that were conducted to evaluate the reliability and internal validity of the HSEBT. Specifically, the purposes were to (i) determine test–retest reliability; (ii) document the inter-rater reliability of all HSEBT reaches; (iii) validate reach measurements (cm and °) collected by a trained physiotherapist against kinematic measurements and (iv) provide reference data for a young healthy male population.

2. Materials and Methods

2.1. Participants

Two convenience samples of 29 (age 25.4 ± 6.4 years; height 180.0 ± 9.3 cm; mean ± SD) and 28 (age 23.8 ± 2.2 years; height 181 ± 6.0 cm; mean ± SD) recreationally active, healthy male subjects volunteered for the reliability analysis and kinematic validation respectively. Exclusion criteria were musculoskeletal or neurological dysfunction or injury in the past six months. All subjects gave written informed consent. The regional committees for medical and health research ethics in Norway (reference number: 2012/1736 A; approval date: 12 October 2012) and Norwegian Data Protection Agency (reference number: 40996) approved the study, and it was carried out according to the rules of the Declaration of Helsinki. The subjects' height and weight were obtained using a Seca model 217 stadiometer and a Seca flat scale (Seca GmbH. & Co., Hamburg, Germany).

2.2. Research Design

Reliability was determined using a within-subjects repeated measures design, while the validation was a cross-sectional study.

2.3. Procedures Hand Reach Star Excursion Balance Test (HSEBT)

The HSEBT consists of eight horizontal and two rotational hand reach tests executed separately standing on the right and the left foot. Similar to the SEBT [3], the horizontal HSEBT reaches are performed along eight reaching directions at 45 degree intervals and categorized into movement patterns according to the following criteria: (1) flexion (three reaches forward to the ground); (2) extension (three reaches backward overhead) and (3) lateral (two reaches laterally overhead).

The two rotational reaches are performed with both shoulders flexed to 90°. Furthermore, hand reaches are classified as either pure plane (reaches within a cardinal plane) or diagonal (reaches that combine planes of motion).

The individual hand reach tests were defined based on the anatomical neutral position as follows: direction (i.e., anterior (A); posterior (P)), side of body (left (L); right (R)); angle at 45° increments from anterior (0°) to posterior (180°); and movement (rotation (ROT)). Thus, pure plane reaches were named A0, P180, R90, L90, LROT and RROT, while diagonal reaches were named R45, R135, L45, and L135. The pure plane and diagonal reaches are bilateral and unilateral hand reaches, respectively. Tables 1 and 2 identify stance foot and hand(s) reaching, while Figure 1 shows the maximum reach positions for all tests. Note that these definitions differ from the SEBT reaching directions defined based on stance foot [3].

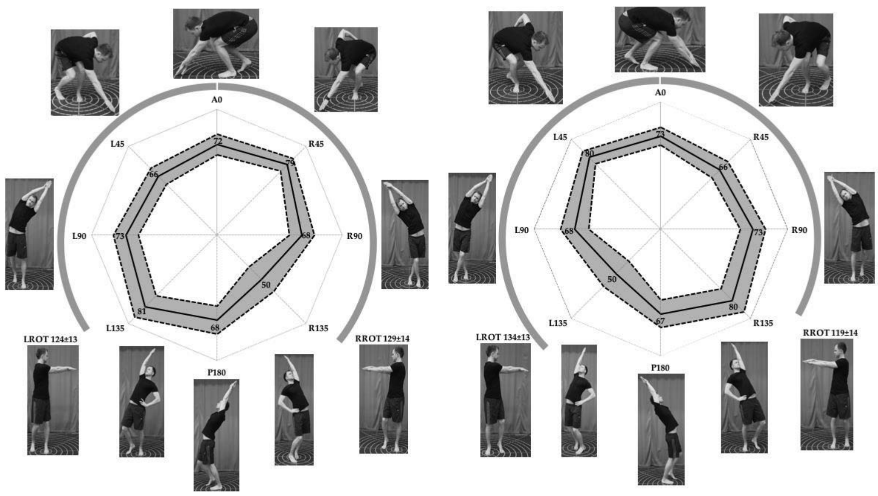

Figure 1. Horizontal and rotational reaches for left and right leg. Visual representation of all reaches (photographs). Horizontal reaches (center graphs) with average (cm, black line) and standard deviation (±SD, grey shaded area). Rotational reaches (°, circular graphs) with average (±SD). All values are based on results from four sessions.

All reaches were performed in the same order (Tables 1 and 2) and testing procedures were based on starting position, movement and measurement. The starting positions were defined as follows: (1) one foot (stance foot) without footwear, positioned in the center of the testing mat; (2) longitudinal axis of stance foot (bisection of heel to second toe) aligned with the A0 to P180 line; (3) other foot (support foot) placed at a 135° angle (toe-touch) relative to the reach vector and rotated in the direction of the reach, with the exception of rotational and lateral movement patterns, where the support foot is oriented in the A0 direction; (4) support foot placed parallel to the stance foot (L90 or R90) for rotational reaches; and (5) diagonal reaches are unilateral hand reaches where the trunk is aligned with the reach vector prior to reaching, and the hand reaching is based on crossing the A0 to P180 line from starting to maximum reach position with the other hand placed on the hip. Movement was defined as follows: (1) the heel and the head of the first and fifth metatarsals of the stance foot maintain ground contact while reaching; (2) elbows extended and wrists in neutral positions; (3) when reaching to the floor (flexion), no weight support with the reaching hand(s) was allowed; and (4) subjects were instructed to reach as far as possible and return to the starting position without losing balance. Measurement was defined as follows: (1) all horizontal reach distances were measured in centimeters (cm) from the center of the mat to the tip of the third digit; (2) rotational reaches were measured in degrees (°); and (3) in extension, lateral, and rotational reaches a plumb line (extension, lateral) or a rod (rotation) was used to project the position of the middle digit to the testing mat. A minimum of three practice trials were given for each reach, after which three valid reaches were recorded, with the maximum value used for analysis.

Similarly to when conducting an SEBT, drawing or taping a star onto the ground to indicate the direction of axes and their scale (cm), with the addition of concentric circles marked at 5° intervals, proved to be a helpful preparation. For ease of measurement, a mat with imprinted reaching directions with marks at 2 cm intervals and nine concentric circles at 10 cm intervals (Athletic Knowledge Nordic AB, Stockholm, Sweden) was used to determine reach performance. The outer concentric circle (90 cm radius) with marks at 5-degree intervals was used to measure rotational reaches.

2.4. Procedure Testing Reliability

Each subject completed the HSEBT a total of four times across four different days. One of three raters (convenience sample) administered the HSEBT independently each day, thus one rater administered the HSEBT twice. Specifically, the rater who tested all subjects twice was a physical therapist with two years' experience in administering the HSEBT, while the other two raters were sports science students with one year of experience. All tests were done independently by each rater, the order of raters was randomized for each subject, and the order of reaches was the same for all sessions (Tables 1 and 2). Testing sessions for each subject were scheduled at the same time of day when possible; 8 a.m.–12 noon (morning) or 12 noon–6 p.m. (afternoon), since time of day has been found to influence performance on a similar test battery (SEBT) [20]. Raters were blinded to inter-rater reliability and test–retest reliability results.

2.5. Procedure Testing Validity

For the validity assessment, the volunteers were equipped with reflective markers to capture movements and postures while executing the HSEBT. The motion tracking system consisted of 15 Oqus cameras (ProReflex®, Qualisys Inc., Gothenburg, Sweden) recording at 480 Hz. A total of seventy-nine spherical reflective markers (20 mm Ø) were attached over specific anatomical landmarks using bi-adhesive tape. For the purpose of validation (cm and °), the following markers were used: foot (calcaneal, 1st and 5th metacarpal marker); leg (medial and lateral malleoli marker); hand (dorsal surface 5th metacarpal marker); upper arm (medial and lateral epicondyle and marker clusters (attached firmly using tensoplast elastic tape (BSN Medical GmBH, Hamburg, Germany)); and the thorax segment (acromion). Markers were identified using Qualisys software (Göteborg, Sweden). Gaps in marker trajectories were interpolated and reconstructed as needed. Otherwise marker data were not treated or filtered.

All HSEBT reaches were recorded on the same testing mat and performed according to the testing procedures described previously, with the exception of the measurements for extension, lateral and rotational movement patterns. These measurement procedures were changed since a tester standing next to the subject obstructed the field of view for multiple cameras, making the tracking of markers difficult. For these movement patterns a vertical pole mounted on a plate was used and moved along the horizontal reach vectors or along the outer concentric circle to the maximum reach position by a tester lying on the floor. The order of tests (Table 3) was the same for all subjects. The maximum reach distance of three trials (Max_m) for each HSEBT reach was used for analysis.

Analysis of kinematic data was done using Visual 3D® (C-Motion Inc., Rockville, MD, USA). Calibration of the kinematic model was carried out using marker locations registered while standing. Local coordinate systems for the foot and upper arm were created according to the International Society of Biomechanics (ISB) recommendations. Specifically, the local foot coordinate system was located at ground level with the origin at the midpoint between the calcaneal marker and the midpoint between the two metacarpal markers to reflect the center of the testing mat. A ZYZ cardan sequence (Z_{first} = horizontal adduction and abduction, Y = abduction and adduction,

Z_{third} = internal and external rotation) was used for orientation of the upper arm segments in the validation of rotational reaches.

Maximum reach events were defined as the position of the ipsilateral metacarpal marker relative to the stance foot in the global coordinate system (orientations: x (+) anterior, y (+) right lateral and z (+) vertical) for the different HSEBT reaches as follows: flexion (minimum z-coordinate value), lateral (minimum and maximum y-coordinate values), extension (minimum z-coordinate value except P180 reaches the minimum x-coordinate value) and rotational movement patterns (minimum x-coordinate value). Reach distances (Max_{kin}) for the horizontal reaches were then calculated from the position of the metacarpal marker at the maximum reach event in the coordinate system of the stance foot. Specifically, Max_{kin} was quantified as $|x|$ and $|y|$ (pure plane reaches) and $\sqrt{(x^2 + y^2)}$ (diagonal reaches). An underestimation of Max_{kin} relative to Max_m is expected for horizontal reaches since the foot coordinate system is not exactly aligned with the center of the testing mat, and the position of the 5th metacarpal marker underestimates the position of the distal-most point of the third digit. Max_{kin} for rotational reaches was defined as the orientation (°) (first rotation (Z) of the ipsilateral upper arm segment) at the maximum reach event resolved in the local coordinate system of the stance foot.

2.6. Statistical Analysis

Descriptive statistics (mean and standard deviation (SD)) were calculated in Excel for Mac OS 10.10.5 (Apple Inc., Cupertino, CA, USA), version 14.4.8 (Microsoft Corp., Redmond, WA, USA) for all tests included in the analysis of inter-rater and test–retest reliability. Specifically, test–retest and inter-rater SDs were calculated using Equations (1) and (2) respectively. All other analyses were done using IBM SPSS version 21.0 (IBM, Armonk, NY, USA). Inter-rater and test–retest reliability were assessed for each test by calculating intraclass correlation coefficients ($ICC_{2,3}$) and ($ICC_{2,1}$) respectively. The following criteria were used to evaluate ICCs: high $\geq$0.90, 0.80–0.89 moderate and below 0.80 questionable. Stability of measurements was assessed by calculating the standard error of measurement (Equation (3)), and the coefficient of variation (CV) for test–retest (Equation (4)) and inter-rater reliability (Equation (5)). Minimal detectable change (MDC_{95}) was calculated for a 95% confidence interval for both test–retest and interrater reliability (Equation (6)). A within-subjects repeated-measures analysis of variance (ANOVA) was performed with the independent variable being day (1, 2, 3, 4) to identify whether any learning effects had occurred between sessions. The same analysis was done with the independent variable being rater (1, 2, 3), where only the first session of the rater who tested the subjects twice was used. The level of significance was set at 95% (α = 0.05).

$$SD_{\text{test-retest}} = \sqrt{\sum}(\text{test 1} - \text{test 2})^2/2n \quad (1)$$

$$SD_{\text{interrater}} = \sqrt{\sum}(SD_{\text{between raters}})^2/n - 1 \quad (2)$$

$$SEM = (SD \times \sqrt{}(1 - ICC) \quad (3)$$

$$SD_{\text{test-retest}}/\text{pooled mean} \times 100 \quad (4)$$

$$SD_{\text{interrater}}/\text{pooled mean} \times 100 \quad (5)$$

$$MDC_{95} = 1.96 \times \sqrt{}(2 \times SEM) \quad (6)$$

The validity of HSEBT reaches was determined by comparing Max_m to Max_{kin} using linear regression analysis and the Bland Altman method. Correlation coefficients of 0.50–0.75 and >0.75 were considered moderate to good and good to excellent, respectively. The normal distribution of difference between measurements (Equation (7)) was assessed using the Shapiro-Wilk test. In the presence of a non-normal distribution of Max_{diff}, a ratio of manual to kinematic measurements was calculated (Equation (8)) and used in the subsequent analysis. Bland Altman plots were then generated for Max_{diff} or r_{m_kin} (y-axis) and averages of measurements (Equation (9)) (x-axis). Bias between measurements ($Max_{diffmean}$) was calculated (Equation (10)) with standard deviation (Max_{diffSD}) and then plotted with

95% confidence interval ($Max_{diffmean} \pm 1.96Max_{diffSD}$). Then standard error difference scores were calculated (Equation (11)). Max_{diff} outliers were determined using the outlier labelling rule of 2.2 multiples of the upper and lower quartiles. Values outside this range were removed from the analysis.

$$Max_{diff} = Max_{m} - Max_{kin} \tag{7}$$

$$r_{m\_kin} = Max_{m}/Max_{kin} \tag{8}$$

$$Max_{mean} = mean(Max_{kin} + Max_{m}) \tag{9}$$

$$Max_{diffmean} = mean_{subject1\text{-}28}Max_{diff} \tag{10}$$

$$SE_{diff} = \sqrt{}(Max_{diffSD}{}^{2}/n) \tag{11}$$

3. Results

There were 6.4 ± 6.1 days between sessions and 63.2% of the test sessions were scheduled at the same time of the day (morning or afternoon) as the previous tests. HSEBT reach tests, ICC, SEM and CV for interrater and test–retest reliability are listed in Table 1, which is organized so that the same tests, left and right, follow each other (grey and white). In addition, HSEBT reach scores (mean ± SD) for all hand reach tests (four sessions) are presented in Figure 1.

Test–retest reliability was moderate to high for 19/20 HSEBT reaches (ICC: 0.80 to 0.96) with right foot L90 reach being questionable (ICC = 0.77). SEM ranged from 0.3 to 2.8 cm and 1.7° to 2.6° for horizontal and rotational reaches respectively, while CV ranged from 2.1% to 13.1%. MDC_{95} ranged from 0.9–7.9 cm and 4.7°–7.2° for horizontal and rotational reaches, respectively (Table 1).

Inter-rater reliability was high (ICC: 0.90 to 0.98) with SEM ranging from 0.3 to 2.1 cm and 1.8° to 2.4° for horizontal and rotational reaches respectively. CV values ranged from 3.1% to 14.6% (Table 1). MDC_{95} ranged from 0.9 to 5.7 cm and 5.1° to 6.6° for horizontal and rotational reaches, respectively (Table 1). There was no effect of test session (day) on the results; however, a significant difference between raters was observed for the following tests (maximum difference between raters identified in parentheses): left foot A0 reach (1.4 cm); right foot L135 reach (5.6 cm); left foot L90 reach (2.6 cm); right foot LROT reach (6.9°); and L foot LROT reach (5.4°) (Table 2).

There was a strong relationship between Max_{m} and Max_{kin} measurements for all HSEBT reaches. Max_{m} and Max_{kin} measurements for 18/20 tests had excellent correlation coefficients ($r \geq 0.90$) and a shared variance of 81 to 97%, while two tests, left foot RROT (r = 0.89) and right foot RROT (r = 0.79), had a shared variance of 79% and 63% respectively (Table 3). Max_{diff} was normally distributed as assessed by Shapiro Wilk's test with one exception, right foot P180 reach (p = 0.045); however, r_{m_kin} for this test was normally distributed (r = 0.067) and used in the agreement analysis (Table 3). There was a positive fixed bias ($Max_{diffmean}$) for all horizontal reaches ranging from 2.2 to 12.8 cm and 23.7% ($r_{m\text{-}kin}$ = 1.237) for the right foot P180 reach test. Fixed biases for the rotational reaches were positive for ipsilateral (10.2 to 11.2°) and negative for contralateral rotational reaches (−5.0 to −6.0°) (Table 3 and Figure 2).

Table 1. Test–retest and inter-rater reliability of hand reach star excursion balance test HSEBT.

Test	Foot	Hand (s)	Order	Test–Retest Reliability							Inter-Rater Reliability						
				Reach (±SD) *	$ICC_{2,1}$	95 CI	$SD_{test-retest}$	SEM *	CV	MDC_{95} *	Reach (±SD) *	$ICC_{2,3}$	95 CI	$SD_{inter-rater}$	SEM *	CV	MDC_{95} *
A0	L	B	3	72 ± 8	0.96	0.92, 0.98	1.5	0.3	2.1	0.9	72 ± 8	0.98	0.95, 0.99	2.2	0.3	3.1	0.9
A0	R	B	4	72 ± 7	0.90	0.79, 0.95	2.3	0.7	3.2	2.1	73 ± 8	0.97	0.95, 0.99	2.3	0.4	3.2	1.1
R45	L	L	1	79 ± 7	0.85	0.71, 0.93	2.6	1.0	3.3	2.8	79 ± 7	0.95	0.90, 0.97	2.9	0.6	3.6	1.8
L45	R	R	2	80 ± 7	0.87	0.74, 0.94	2.4	0.9	3.0	2.4	80 ± 7	0.95	0.90, 0.97	2.8	0.6	3.5	1.7
R90	L	B	9	68 ± 10	0.82	0.65, 0.91	4.4	1.9	6.5	5.1	68 ± 10	0.95	0.91, 0.98	3.8	0.8	5.6	2.3
L90	R	B	10	68 ± 10	0.87	0.73, 0.94	3.9	1.4	5.8	3.9	68 ± 11	0.95	0.91, 0.98	3.9	0.9	5.8	2.4
R135	L	L	15	50 ± 13	0.80	0.61, 0.90	6.4	2.8	12.8	7.9	49 ± 14	0.91	0.84, 0.96	6.6	2.0	13.4	5.5
L135	R	R	16	49 ± 15	0.84	0.69, 0.92	6.5	2.6	13.1	7.2	50 ± 14	0.92	0.85, 0.96	7.3	2.1	14.6	5.7
P180	L	B	13	67 ± 12	0.87	0.74, 0.94	4.3	1.6	6.4	4.3	69 ± 11	0.96	0.92, 0.98	3.9	0.8	5.7	2.2
P180	R	B	14	67 ± 11	0.80	0.61, 0.90	5.1	2.3	7.6	6.3	67 ± 11	0.93	0.88, 0.97	4.8	1.3	7.2	3.5
L135	L	R	11	80 ± 12	0.87	0.74, 0.94	4.2	1.5	5.2	4.2	81 ± 12	0.93	0.87, 0.97	5.4	1.4	6.6	3.9
R135	R	L	12	80 ± 14	0.90	0.80, 0.95	4.5	1.4	5.6	3.9	80 ± 13	0.95	0.90, 0.97	5.4	1.2	6.7	3.3
L90	L	B	7	73 ± 10	0.84	0.69, 0.92	4.0	1.6	5.5	4.5	74 ± 11	0.92	0.84, 0.96	5.2	1.4	7.0	4.1
R90	R	B	8	72 ± 10	0.77	0.57, 0.89	4.8	2.3	6.6	6.3	74 ± 11	0.93	0.86, 0.96	4.9	1.3	6.7	3.6
L45	L	R	5	65 ± 9	0.94	0.87, 0.97	2.2	0.5	3.4	1.5	66 ± 9	0.96	0.92, 0.98	3.3	0.7	5.0	1.8
R45	R	L	6	66 ± 8	0.91	0.82, 0.96	2.5	0.8	3.8	2.1	66 ± 9	0.95	0.91, 0.97	3.5	0,8	5.2	2.1
RROT	L	B	17	129 ± 13	0.87	0.74, 0.94	4.7	1.7	3.6	4.7	128 ± 14	0.92	0.85, 0.96	6.5	1.8	5.1	5.1
LROT	R	B	18	134 ± 13	0.86	0.72, 0.93	5.0	1.9	3.8	5.2	130 ± 13	0.90	0.81, 0.95	7.5	2.4	5.8	6.6
LROT	L	B	19	124 ± 14	0.84	0.68, 0.92	5.7	2.3	4.6	6.3	121 ± 15	0.93	0.86, 0.96	7.1	1.9	5.8	5.2
RROT	R	B	20	119 ± 14	0.82	0.66, 0.91	6.1	2.6	5.1	7.2	118 ± 16	0.93	0.88, 0.97	7.0	1.8	5.9	5.1

* = cm is the unit in all reach tests with the exception of LROT and RROT where ° is the measurement unit. Abbreviations: ICC = Interclass correlation coefficient; SD = Standard deviation; SEM = Standard error of measurement (cm/°); CV = Coefficient of variation (%); MDC_{95} = Minimal detectable change; L = Left; R = Right; B = Bilateral; A0 = Anterior (0°) reach; R45 = Right anterolateral (45°) reach; R90 = Right lateral (90°) reach; R135 = Right posterolateral (135°) reach; P180 = Posterior (180°) reach; L135 = Left posterolateral (135°) reach; L90 = Left lateral (90°) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach.

Table 2. Effect of day and tester on HSEBT measurements.

Test	Foot	Hand (s)	Order	Effect of Day					Effect of Tester			
				Day 1 *	Day 2 *	Day 3 *	Day 4 *	Wilks Lambda (p)	Tester 1 *	Tester 2 *	Tester 3 *	Wilks Lambda (p)
A0	L	B	3	72.8 ± 7.4	72.2 ± 7.9	72.2 ± 7.5	71.9 ± 8.4	0.587	72.3 ± 7.6	71.7 ± 7.9	73.1 ± 8.1	0.048 *
A0	R	B	4	72.7 ± 7.6	73.1 ± 7.7	72.4 ± 6.8	72.0 ± 8.1	0.569	72.4 ± 7.4	72.1 ± 7.1	73.5 ± 8.3	0.057
R45	L	L	1	79.9 ± 6.9	79.2 ± 7.5	79.6 ± 7.1	78.5 ± 7.5	0.071	79.1 ± 6.6	79.2 ± 8.1	80.0 ± 7.3	0.277
L45	R	R	2	81.1 ± 6.5	79.6 ± 7.6	80.3 ± 7.0	79.2 ± 7.6	0.054	80.1 ± 6.3	79.7 ± 8.1	80.8 ± 7.2	0.132
R90	L	B	9	67.8 ± 9.8	67.3 ± 10.3	68.4 ± 10.3	67.7 ± 10.4	0.625	67.7 ± 11.0	68.5 ± 10.1	67.4 ± 9.9	0.479
L90	R	B	10	68.2 ± 10.8	67.3 ± 11.0	69.0 ± 9.8	66.9 ± 11.5	0.154	68.5 ± 10.8	67.8 ± 10.1	68.1 ± 12.0	0.768
R135	L	L	15	46.6 ± 13.1	50.0 ± 14.1	50.5 ± 12.7	52.2 ± 14.1	0.055	48.1 ± 13.4	49.2 ± 13.1	50.6 ± 14.6	0.397
L135	R	R	16	47.7 ± 13.8	50.1 ± 14.6	50.5 ± 14.4	52.5 ± 15.4	0.219	47.0 ± 14.3	49.9 ± 14.6	52.6 ± 14.4	0.032 *
P180	L	B	13	69.6 ± 11.1	67.7 ± 11.4	68.0 ± 10.4	67.9 ± 12.1	0.225	68.1 ± 12.0	69.3 ± 11.1	69.0 ± 10.5	0.403
P180	R	B	14	66.3 ± 11.5	66.4 ± 11.5	67.5 ± 11.4	67.4 ± 10.9	0.539	66.2 ± 11.9	67.1 ± 10.9	67.1 ± 11.7	0.713
L135	L	R	11	82.3 ± 11.2	79.5 ± 13.1	80.7 ± 10.9	81.2 ± 12.5	0.261	79.5 ± 12.1	82.3 ± 11.2	81.9 ± 12.8	0.061
R135	R	L	12	80.7 ± 13.7	79.0 ± 14.5	80.6 ± 12.2	81.5 ± 13.3	0.256	78.8 ± 13.9	80.7 ± 13.1	81.5 ± 13.4	0.144
L90	L	B	7	73.3 ± 10.8	72.1 ± 10.7	74.8 ± 10.7	73.4 ± 9.9	0.081	72.3 ± 10.5	74.9 ± 9.4	73.5 ± 12.1	0.044 *
R90	R	B	8	75.1 ± 9.3	71.5 ± 11.5	74.1 ± 10.0	72.2 ± 10.3	0.063	72.1 ± 10.9	74.6 ± 9.7	74.0 ± 11.3	0.166
L45	L	R	5	65.7 ± 8.8	65.6 ± 8.6	66.5 ± 9.4	65.2 ± 9.4	0.463	65.4 ± 9.3	66.0 ± 9.1	66.4 ± 9.4	0.441
R45	R	L	6	65.0 ± 8.9	65.8 ± 8.2	66.7 ± 8.8	65.9 ± 9.4	0.466	65.5 ± 8.9	65.6 ± 9.2	66.6 ± 9.2	0.458
RROT	L	B	17	127.8 ± 14.4	128.2 ± 14.4	127.9 ± 11.8	128.6 ± 12.6	0.942	129.0 ± 14.2	126.4 ± 13.0	127.8 ± 13.7	0.289
LROT	R	B	18	130.6 ± 13.4	131.3 ± 15.2	129.6 ± 10.6	132.4 ± 13.6	0.306	134.0 ± 14.0	127.1 ± 11.5	129.7 ± 13.8	0.002 *
LROT	L	B	19	121.0 ± 15.4	121.6 ± 14.2	121.6 ± 13.3	121.7 ± 15.9	0.979	122.9 ± 14.2	117.5 ± 14.9	121.4 ± 15.0	0.016 *
RROT	R	B	20	117.8 ± 16.1	118.4 ± 14.9	119.0 ± 13.4	117.7 ± 16.7	0.797	118.1 ± 15.1	115.0 ± 15.9	119.9 ± 15.8	0.250

* = cm is the unit in all reach tests with the exception of LROT and RROT where ° is the measurement unit. Abbreviations: L = Left; R = Right; B = Bilateral; A0 = Anterior (0°) reach; R45 = Right anterolateral (45°) reach; R90 = Right lateral (90°) reach; R135 = Right posterolateral (135°) reach; P180 = Posterior (180°) reach; L135 = Left posterolateral (135°) reach; L90 = Left lateral (90°) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach.

Table 3. Validity of HSEBT.

Test	Foot	Hand(s)	Order	Max_m (±SD) [a]	Max_{kin} (±SD) [a]	Regression Analysis		Agreement Analysis	
						r	R^2	Bias ± SD	Bias ± SE
A0	L	B	9	72.8 ± 8.4	70.6 ± 6.9	0.97	0.94	2.2 ± 2.4	2.2 ± 0.5
A0	R	B	15	71.2 ± 9.9	67.8 ± 8.4	0.98	0.96	3.4 ± 2.3	3.4 ± 0.5
R45	L	L	1	79.0 ± 7.2	74.1 ± 6.6	0.95	0.90	4.9 ± 2.4	4,9 ± 0.4
L45	R	R	5	79.2 ± 8.4	74.1 ± 6.9	0.96	0.93	5.1 ± 2.6	5.1 ± 0.5
R90	L	B	12	67.4 ± 11.2	55.3 ± 10.5	0.96	0.92	12.0 ± 3.1	12.0 ± 0.6
L90	R	B	18	67.6 ± 12.3	54.7 ± 11.1	0.95	0.91	12.8 ± 3.8	12.8 ± 0.7
R135	L	L	4	62.0 ± 13.3	52.2 ± 12.3	0.95	0.89	9.8 ± 4.4	9.8 ± 0.8
L135	R	R	8	61.3 ± 14.3	50.2 ± 14.3	0.99	0.97	11.1 ± 2.4	11.1 ± 0.5
P180	L	B	10	71.3 ± 12.9	58.5 ± 12.4	0.97	0.94	12.8 ± 3.1	12.8 ± 0.6
P180	R	B	16	70.8 ± 12.4	57.7 ± 11.9	0.95	0.91	1.237 ± 0.087 [b]	1.237 ± 0.016 [b]
L135	L	R	2	87.6 ± 8.9	76.6 ± 8.6	0.95	0.91	11.0 ± 2.7	11.0± 0.5
R135	R	L	6	82.8 ± 10.7	73.1 ± 9.9	0.94	0.88	9.7 ± 3.7	9.7± 0.7
L90	L	B	11	75.7 ± 10.0	71.8 ± 7.6	0.90	0.81	3.8 ± 4.6	3.8 ± 0.9
R90	R	B	17	74.5 ± 11.6	69.5 ± 9.5	0.95	0.90	5.1 ± 4.0	5.1 ± 0.8
L45	L	R	3	68.2 ± 9.5	65.0 ± 8.1	0.99	0.98	3.2 ± 1.9	3.2 ± 0.4
R45	R	L	7	65.7 ± 9.9	63.0 ± 8.6	0.98	0.96	2.7 ± 2.3	2.7 ± 0.4
RROT	L	B	14	135.4 ± 14.8	140.4 ± 16.0	0.89	0.79	−5.0 ± 7.3	−5.0 ± 1.4
LROT	R	B	20	140.8 ± 15.1	146.8 ± 19.4	0.90	0.81	−6.0 ± 8.8	−6.0 ± 1.7
LROT	L	B	13	133.3 ± 18.7	123.1 ± 18.9	0.92	0.84	10.2 ± 7.7	10.2 ± 1.5
RROT	R	B	19	135.2 ± 15.5	124.0 ± 16.3	0.79	0.63	11.2 ± 10.3	11.2 ± 2.0

[a] = cm is the unit in all reach tests with the exception of LROT and RROT where is the measurement unit. [b] = bias as ratio (r_{m_kin} = Ratio Max_m/Max_{kin}). Abbreviations: SD = Standard deviation; SE = Standard error; Max_m = Maximum observed HSEBT reach measurement; Max_{kin} = Maximum measured kinematic measurement; *r* = Correlation coefficient; R^2 = Coefficient of determination; L = Left; R = Right; B = Bilateral; A0 = Anterior (0°) reach; R45 = Right anterolateral (45°) reach; R90 = Right lateral (90°) reach; R135 = Right posterolateral (135°) reach; P180 = Posterior (180°) reach; L135 = Left posterolateral (135°) reach; L90 = Left lateral (90°) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach.

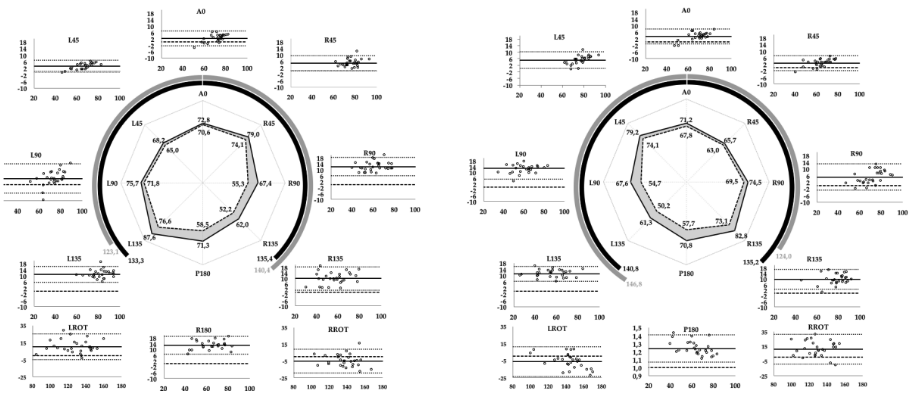

Figure 2. Agreement analysis of horizontal and rotational reaches left and right foot. Visual representation (center left and right) of horizontal reach test scores (full line Max_m, dotted line Max_{kin} and grey area showing difference). Circular graphs (Max_{kin} grey, Max_m black) of left and right rotational reaches. Bland Altman plots (*y*-axis: Max_{diff} (cm) and *x*-axis: Max_{mean} (cm)) for all tests with fixed bias (full line) with 95% confidence interval (dotted line) and agreement (dashed line).

4. Discussion

The current study has established the HSEBT as a reliable and valid test battery for hand reaches, with description of the testing procedures and reference values for a young, healthy male population. The HSEBT has moderate to high test–retest and inter-rater reliability, with ICC results similar to or better than comparable tests such as SEBT [21] and functional reach test (FR) [22]. Response stability (SEM and CV) was also comparable to these tests [16,21,22], while MDC_{95} was smaller than what has been reported for the SEBT [23]. No learning effect between test sessions was observed, but there was a small yet systematic difference between raters in five tests. Manual (Max_m) and calculated (Max_{kin}) hand reach measurements had good to excellent correlation. However, agreement analysis showed a fixed bias for all HSEBT reaches, which can be partially explained by the methods used for kinematic calculation (Max_{kin}).

The reliability results (ICC values) obtained in the current study are comparable to other tests of dynamic postural control and functional mobility. The HSEBT test–retest reliability ICC values ranged from 0.77 to 0.96, while FR test–retest reliability ICC values of 0.89 and 0.92 have been reported [16,22]. Upper quarter Y balance tests and the multi-directional reach tests were found to range from 0.80 to 0.99 [19] and 0.93 to 0.95 [13], respectively. SEBT ICC test–retest values range from 0.84 to 0.98 [23–26]. Furthermore, the inter-rater reliability of the HSEBT was high, with ICC values ranging from 0.90 to 0.98. FR inter-rater ICC values between 0.73 and 0.98 have been reported [22,27,28], while SEBT values range from 0.81 to 0.93 [21,24,26,29]. Even though our ICC results showed high HSEBT inter-rater reliability, the repeated measure ANOVA results suggested that in five of the 20 tests at least one rater differed systematically from the other raters (Table 2). Effects of test administrators on the results therefore cannot be ruled out. In contrast, test day did not have an impact on the results (Table 2).

Response stability, as quantified by SEM, ranged in the current study from 0.3 to 2.8 cm and from 1.7° to 2.6° for both test–retest and interrater reliability. The SEM values reported for the SEBT range from 2.2 to 4.8 cm and 2.0 to 5.0 cm for test–retest and inter-rater reliability, respectively [21,23,30], while FR ranged from 2.1 to 4.0 cm and 2.1 to 4.3 cm for inter-rater and test–retest reliability, respectively [22]. In summary, the SEM values found for HSEBT are comparable or lower than those established for the SEBT and FR.

However, CV is a more appropriate measure of response stability than SEM when comparing HSEBT to SEBT and FR. In the current study the CV ranged from 2.1% to 13.1% and 3.1% to 14.6% for test–retest and inter-rater reliability, respectively. Some of these values are higher than the test–retest CVs reported for the SEBT, 2.0% to 4.6% [25], and the FR, 2.5% [16]. One potential reason for these relatively large variations is the influence of visual feedback. When subjects could see how far they reached (flexion) a considerably lower variation was observed (test–retest CV: 2.1–3.8%; inter-rater CV: 3.1–5.2%), than when the subjects were blind to the test results (lateral and extension) (test–retest CV: 5.2–13.1%; inter-rater CV: 5.6–14.6%).

MDC values are change scores important from both a clinical and a research perspective. MDC_{95} for the horizontal and rotational reaches ranged from 0.9 to 7.9 cm and 4.7° to 7.2° respectively for both inter-rater and test–retest reliability (Table 1). Based on clinical experience, a 5 cm change in flexion and 7 cm change in lateral and extension movement patterns have been considered clinically meaningful in documenting change or right-to-left asymmetry. However, our results suggest that mostly lower values, 0.9 to 2.8 cm, 2.3 to 6.3 cm, and 2.2 to 7.9 cm, can be used in flexion, lateral and extension movement patterns respectively (Table 1). Based on our findings and clinical experience we recommend 5 cm in flexion and 7 cm in lateral and extension movement patterns as a clinically meaningful difference. These values are comparable to what has been reported for the SEBT (5–7 cm) [23], while others have found slightly greater values [24]. In their discussion, Munro and co-workers argue that an MDC of 5–7 cm (6–8% of leg length) puts into question previously established side differences of 4.2 cm and 2–5% in patients with and without chronic ankle instability (CAI) [23], as well as the 4 cm SEBT side difference used to determine risk of lower extremity injury in high school basketball players [25].

There was a good to excellent relationship between Max_m and Max_{kin} measurements, similar standard deviations, and a shared variance ranging from 63% to 97% for all HSEBT reaches. However, agreement analysis using the Bland Altman method found a fixed bias for all tests, which can be partially explained by the position of the center of the foot coordinate system relative to the geometric center of the foot, and the orientation of the hand at maximum reach position. The observed differences in fixed biases for the horizontal reaches ranged from 2.2 to 5.1 cm, 3.8 to 12.8 cm and 9.7 to 12.8 cm (Table 3) for flexion, lateral and extension movement patterns, respectively. The difference between flexion and extension movement patterns can be partially explained by the definition of the foot coordinate system. The center of the foot coordinate system will be posterior to the geometrical center of the foot used as a reference for foot placement on the testing mat. This will decrease and increase the influence of the distance (cm) from the 5th metacarpal marker to the distal-most point of the third digit in flexion and extension movement patterns, respectively, based on the assumption of similar hand orientation. The influence of hand orientation can be exemplified and may partially explain the observed differences between lateral movement patterns. There were directional specific differences in the fixed bias for ipsilateral and contralateral overhead reaches of 3.8 to 5.1 cm and 12.0 to 12.8 cm, respectively. The hand had a stronger vertical orientation in the maximum reach position in the ipsilateral than in the contralateral overhead reach (visual observation). Thus, the 5th metacarpal marker will better approximate the position of the distal-most point of the third digit (y-coordinate) in the ipsilateral than in the contralateral overhead reach. Fixed bias for rotational reaches can be partially explained by the orientation of the ipsilateral upper arm to the stance foot at the maximum reach event. Max_{kin} values were higher and lower than Max_m for contralateral and ipsilateral rotational reaches, respectively. A greater contribution of shoulder horizontal adduction in contralateral rather than horizontal abduction in ipsilateral rotational reaches (visual observation) can explain the observed difference. Based on the good to excellent correlation coefficients between Max_m and Max_{kin}, and because kinematic methods can explain the observed fixed biases, manual measurements of hand reach distance (cm) and rotation (°) seem valid.

4.1. Clinical Application

Future research should focus on the HSEBT as a clinical measure for dynamic postural control and functional joint mobility testing in different populations. In particular, the application of HSEBT, possibly in combination with SEBT, should be explored in sports where hand and arm action is closely linked with the movement of the rest of body, such as volleyball, tennis, golf and various throwing sports. Furthermore, different reach directions describe different limits of stability [13] and since falls often occur while reaching [15] HSEBT may be an interesting clinical tool in determining fall risks. In addition, the ability to assess the influence of other joints and regions on specific diagnoses such as low back pain (LBP) and shoulder instability has the potential to offer information about causative factors. We also believe that the HSEBT is a clinical measure that has the potential to differentiate pathological conditions, similar to the SEBT. The HSEBT may serve as a weight-bearing version of current clinical tests; for example, the L foot L45/R foot R45 triggers the same hip joint movements (flexion, adduction and internal rotation) that comprise a clinical test for hip impingement (FADIR).

4.2. Study Limitations

In future studies, learning effects, rest periods, and the randomization of reach orders and populations should be addressed. Each subject was given at least three warm-up attempts per reach. These were not documented and more attempts were given if the subjects were unable to complete the reach as defined by the testing procedures. Documentation of warm-up reaches could have provided additional information about learning effects. Future studies should include females, a wider age-range and different diagnoses, since only a young, healthy, male population was studied. However, the current study provides reference data that can be used for future comparisons.

The kinematic methods used to calculate maximum reach position could be improved since a fixed bias was observed for all tests. Placement of a marker at the distal-most point of the third digit of the reaching hand, and using an external reference frame (markers) with a geometrical center in the center of the mat, rather than the coordinate system of the foot, would have optimized kinematic distance calculations. In addition, the pole used to measure lateral and extension movement patterns introduced a measurement error, because the center of the base of the pole (4 cm diameter) had to be projected onto the reaching vector. However, this was necessary since the presence of a tester standing next to the subject obstructed the view of the markers used for kinematic analysis.

5. Conclusions

HSEBT has moderate to high intra-test and test–retest reliability (ICC) and stability of measurements (SEM, CV and MDC_{95}) similar to or better than comparable tests such as SEBT and FR. Manually obtained HSEBT reach test measurements (cm or °) are a valid representation of calculated measurements. However, the fixed bias observed for all tests, partially explained by the kinematic methods employed, has to be considered in the interpretation of internal validity. Since the HSEBT elicits joint movements in the hip, spine and shoulder, which are not challenged to the same magnitude in other dynamic postural control tests, it can be considered a viable complement to these tests. We expect that the HSEBT will find application in the clinical assessment and documentation of training and rehabilitative progress for shoulder, spine, hip and knee musculoskeletal dysfunctions, as well as in LBP, and neurological conditions with balance and dynamic postural control impairments.

Acknowledgments: The authors would like to thank Vidar Eivind Jakobsen, Patrick Anderson and Eirik Andreassen for technical support during motion capture; Ingar Holme for statistical advice; Jens Bojsen-Møller and Olivier Seynnes for valuable advice on methods and organization of the manuscript; and Ali Ghelem and Jessica Parnevik-Muth for assisting in the development of the HSEBT.

Author Contributions: Ola Eriksrud conceived the HSEBT and designed the experiments. Ola Eriksrud, Fredrik Sæland and Stavros Litsos performed the experiments. Ola Eriksrud and Jan Cabri analyzed the data. Ola Eriksrud, Peter Federolf and Jan Cabri wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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Paper II

PLOS ONE

RESEARCH ARTICLE

Hand reach star excursion balance test: An alternative test for dynamic postural control and functional mobility

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Citation: Eriksrud O, Federolf P, Anderson P, Cabri J (2018) Hand reach star excursion balance test: An alternative test for dynamic postural control and functional mobility. PLoS ONE 13(5): e0196813. https://doi.org/10.1371/journal.pone.0196813

Editor: Stefan Josef Lindinger, University of Salzburg, AUSTRIA

Received: August 31, 2017

Accepted: April 22, 2018

Published: May 8, 2018

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Data Availability Statement: Data kept in Harvard Dataverse (doi:10.7910/DVN/URE9U1).

Funding: None of the authors, including the first author, received any commercial funding or salary that would influence the study design, data collection and analysis, decision to publish, or preparation of the manuscript. The specific roles of these authors are articulated in the 'author contributions' section.

Competing interests: I have read the journal's policy and the authors of this manuscript have the following competing interests: The first author is a

Abstract

Tests of dynamic postural control eliciting full-body three-dimensional joint movements in a systematic manner are scarce. The well-established star excursion balance test (SEBT) elicits primarily three-dimensional lower extremity joint movements with minimal trunk and no upper extremity joint movements. In response to these shortcomings we created the hand reach star excursion balance test (HSEBT) based on the SEBT reach directions. The aims of the current study were to 1) compare HSEBT and SEBT measurements, 2) compare joint movements elicited by the HSEBT to both SEBT joint movements and normative range of motion values published in the literature. Ten SEBT and HSEBT reaches for each foot were obtained while capturing full-body kinematics in twenty recreationally active healthy male subjects. HSEBT and SEBT areas and composite scores (sum of reaches) for total, anterior and posterior subsections and individual reaches were correlated. Total reach score comparisons showed fair to moderate correlations (r = .393 to .606), while anterior and posterior subsections comparisons had fair to good correlations (r = .269 to .823). Individual reach comparisons had no to good correlations (r = -.182 to .822) where lateral and posterior reaches demonstrated the lowest correlations (r = -.182 to .510). The HSEBT elicited more and significantly greater joint movements than the SEBT, except for hip external rotation, knee extension and plantarflexion. Comparisons to normative range of motion values showed that 3 of 18 for the SEBT and 8 of 22 joint movements for the HSEBT were within normative values. The findings suggest that the HSEBT can be used for the assessment of dynamic postural control and is particularly suitable for examining full-body functional mobility.

Introduction

Different tests of dynamic postural control have gained popularity and interest since they are considered more ecological in sports or physical activities [1]. One such test is the star excursion balance test (SEBT) which was originally presented as a low-cost rehabilitation tool [2]. The SEBT quantifies maximum foot reach distances of the non-stance foot using a star on the co-founder of Athletic Knowledge AB (Stockholm, Sweden) which commercially distributes a testing mat for the SEBT or HSEBT. This does not alter our adherence to PLOS ONE policies on sharing data and materials.

ground with 8 different reaching directions at 45-degree intervals extending from a center point [3]. Currently, the star excursion balance test (SEBT) is a well-established task-based objective clinical test battery of dynamic postural control that measures different aspects of neuromuscular functions, such as proprioception [4], strength [5–7], power [8], balance [6] and coordination [9] while eliciting different combinations of trunk and lower extremity joint movements [10–14]. Clinical application of the SEBT has primarily focused on lower extremity joint dysfunctions such as ankle instability, knee dysfunction after anterior cruciate ligament reconstruction, patella femoral pain and in the prediction lower extremity injuries [1]. The SEBT is frequently described as a "series of single leg squats" [1], and is therefore not well suited to capture movements in the transverse plane, as is reflected by elicited hip rotational joint movements [10, 12, 15]. Furthermore, SEBT neither captures all hip joint movements nor does it represent the interaction of larger trunk and upper extremity joint movements.

Complementing the SEBT with hand reaches is a justifiable approach to reduce these shortcomings. However, current hand reach tests also have shortcomings since they are performed in bilateral stance and elicit neither large joint movements nor vertical displacement of the center of mass (COM) [16–18]. Hand reaches based on SEBT reaching directions, the "hand reach star excursion balance test" HSEBT [19], may provide a platform in which upper extremity and greater trunk movements are integrated with lower extremity joint movements. Consequently, the HSEBT can complement the clinical application of the SEBT by addressing full body movements in the assessment of dynamic postural control. In addition, these hand reach tests can also serve as a measure of functional mobility, i.e. the combination of range of motion (ROM) of multiple joints utilized to accomplish more ecological activities of daily living and athletic performance. If HSEBT reaches are to be a measure of functional mobility they should elicit more and greater joint movements than their SEBT counterparts. Also, the elicited joint movements from the HSEBT should be more comparable to established normative ROM goniometric reference data, indicating that mobility is being challenged. Thus, information obtained from HSEBT reaches can provide clinicians with a systematic assessment tool to better understand the influence of dysfunction such as shoulder instability [20] and low back pain (LBP) [21] on full body movements.

The purpose of the current study was to 1) determine if the HSEBT reaches provide different information about dynamic postural control than the SEBT reaches, and 2) compare joint movements elicited by HSEBT to both SEBT and normative joint mobility (ROM) values published in the literature.

Materials and methods

Participants

A convenience sample of twenty recreationally active healthy male subjects (age 24.4 ± 2.3 years; height 179.9 ± 6.0 cm; weight 77.5 ± 9.3 kg; mean ± SD) volunteered for the study. Exclusion criteria were musculoskeletal or neurological dysfunction or injury in the past six months. Body height and weight were obtained using a Seca model 217 stadiometer and a Seca flat scale (Seca GmbH. & Co. Hamburg. Germany).

Ethics approval. The committee for medical and health research ethics in Norway (2012/1736) and Norwegian Data Protection Agency (40996) approved the study. Measurements were carried out according to the principles described in the Declaration of Helsinki. All subjects were given written and verbal information about the study prior to giving written informed consent. The individual in this manuscript has given written informed consent (as outlined in PLOS consent from) to publish these case details.

Experimental design

Descriptive and cross-sectional cohort study for comparison of HSEBT and SEBT reach tests.

Procedures

The HSEBT consists of 10 hand reaches on each foot (stance foot) with toe-touch of the opposite foot in the same 8 directions as used for the SEBT with the addition of two rotational reaches. HSEBT reaching directions are defined from the anatomical neutral position as follows: direction (i.e.: anterior (A); posterior (P)), side of body (left (L); right (R)), angle at 45˚ increments from anterior (0˚) to posterior (180˚) and movement (rotation (ROT)). Reaches along the 8 horizontal reach vectors (A0, R45, R90, R135, P180, L135, L90 and L45) are horizontal reaches (HR) and measured in centimeters (cm), while the two rotational reaches (LROT, RROT) are measured in degrees (˚). These reach definitions were applied to the SEBT for ease of comparison, which differs from established SEBT definitions based on stance foot [3]. Furthermore, two rotational reaches were added to the SEBT to complement the HSEBT rotational reaches, and to target transverse plane dynamic postural control in single leg stance. Both HSEBT and SEBT reaches can be classified based on plane(s) of motion: pure plane (A0, P180, L90, R90, LROT, RROT) and diagonal (L45, R45, L135, R135); or with subgroups based on direction of movement: anterior (L45, A0, R45), posterior (L135, P180, R135), lateral (L90, R90), and rotational (LROT, RROT).

HSEBT and SEBT reaches were performed in the same order and executed on a testing mat, which was developed to guide and measure the different reaches. The mat was imprinted with horizontal reaching directions marked at 2 cm intervals and with nine concentric circles at 10 cm intervals marked at 5-degree intervals (Athletic Knowledge Nordic AB, Stockholm, Sweden). Both the HSEBT and SEBT testing procedures are described in detail elsewhere [3, 19]. The following clarifications concerning the SEBT need to be made:1) the stance foot was placed on the middle of the mat, 2) heel, first and fifth metatarsal heads maintained ground contact during the reaches, 3) the trunk aligned with the reach vector for diagonal reaches (R45, R135, L135 and L45); 4) the lateral reaches (R foot L90 and L foot R90 reach) were performed with the reaching foot in front of stance foot, and additionally 5) during rotational reach the big toe of the reaching foot followed the 50 cm radius circle with its longitudinal axis oriented toward the center of the testing mat. For all HSEBT and SEBT reaches a minimum of three practice trials were allowed, after which three valid maximum reaches were recorded of which the highest value was used for analysis. Trials were discarded if the procedures were not followed.

Kinematic data of all reaches were obtained using 15 Oqus cameras (ProReflex®, Qualisys Inc., Gothenburg, Sweden) recording at 480 Hz. Fifty-eight spherical reflective markers (20 mm Ø) were attached over specific anatomical landmarks (Fig 1) to define and track the foot, leg, thigh, pelvis, thorax and upper arm segments. The marker clusters used for the leg, thigh and upper arm were attached firmly using tensoplast elastic tape (BSN Medical GmBH, Hamburg, Germany). The markers were identified using the Qualisys software (Qualisys Inc., Gothenburg, Sweden). To minimize the risk of gaps in marker trajectories, especially for the anterior trunk and pelvic markers during anterior reaches (L45, A0 and R45), lateral pelvic markers were included in the marker set for tracking and four Qualisys cameras were placed as close to the ground as possible. If gaps in marker trajectories occurred, they were interpolated or reconstructed [22]. However, these methods sometimes failed with a minimum number of subjects included for HSEBT shoulder (14), trunk (19), hip (20), knee (19) and foot (20) joint movement calculations. All joint movement calculations for the SEBT included all subjects, except for LROT (19) and RROT (18). Otherwise, the marker data were not treated or filtered.

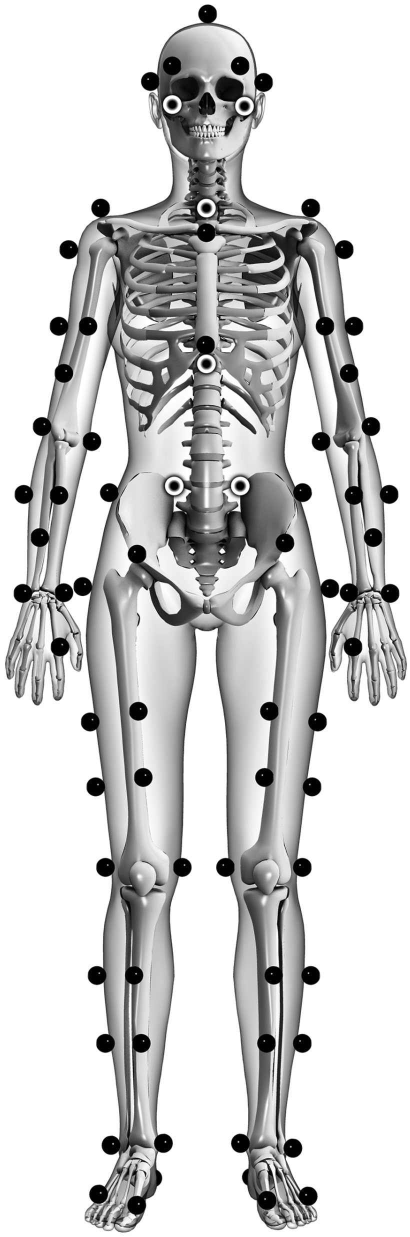

Fig 1. Marker set used for kinematic data acquisition.

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Data analysis

The data analysis was carried out using Visual 3D® (C-Motion Inc., Rockville, MD, USA). Local coordinate systems for the foot, leg, thigh, pelvis, thorax and upper arm were created [23, 24]. Three-dimensional joint rotations of the ankle, knee, hip and trunk were then calculated (cardan sequence XYZ). Shoulder motions were calculated using both ZYZ (Z_{first} = horizontal adduction and abduction, Y = abduction and adduction, Z_{third} = internal and external rotation) and XYZ (X = flexion and extension) cardan sequences. Prior to reaching the subjects were asked to stand feet parallel to shoulder line with hands on the hips for a minimum of 3 seconds. Normalization of joint starting positions was defined as the mean joint positions observed during the last 95 of the first 100 frames of recording (ϕ_{start}) (Eq 1).

$$\phi_{start} = mean_{frames\ 5-100} \tag{1}$$

The local coordinate system of the upper arm was aligned with the thorax at the beginning of each motion trial, and was used for all joint angle calculations of the shoulder. Furthermore, the neutral starting position for shoulder horizontal abduction and adduction was defined as the upper arm oriented in the frontal plane (90˚ abducted position). Maximum reach position (ϕ_{max}) was defined as the highest (or lowest) x, y and z-coordinate values in the global coordinate system of the second metacarpal and the first metatarsal marker of the reaching hand or foot, respectively, with procedures described in detail elsewhere [19]. All tests were visually inspected to ensure that the set criteria matched for ϕ_{max}. Joint movements (θ) were then calculated (Eq 2) for each reach and averaged for all subjects.

$$\theta = \phi_{max} - \phi_{start} \tag{2}$$

Joint movements of mirrored reaches (left and right) were averaged and named based on left stance foot definitions for ease of data presentation. In tests with bilateral symmetrical shoulder joint movements, i.e. A0, P180, L90 and R90 reaches, only the mean of left and right shoulders is presented. Reaches eliciting the greatest values in joint movements (θ_{max}) of the ankle foot complex, knee, hip, trunk and shoulder were identified for both the HSEBT ($\theta_{maxHSEBT}$) and SEBT ($\theta_{maxSEBT}$) and their differences were calculated ($\theta_{maxDIFF}$) (Eq 3).

$$\theta_{maxDIFF} = \theta_{maxHSEBT} - \theta_{maxSEBT} \tag{3}$$

Then, $\theta_{maxHSEBT}$ and $\theta_{maxSEBT}$ values were compared to determine if they were within a 95% confidence interval of normative ROM reference [25], except knee rotations and trunk movements (lumbar and thoracic spine values added) were compared to the lowest reported values [26]. Comparisons of $\theta_{maxHSEBT}$ and $\theta_{maxSEBT}$ ankle and knee abduction and adduction were not done since these measures are not commonly quantified using clinically available assessment tools and normative clinical ROM values are lacking [25]. Shoulder $\theta_{maxHSEBT}$ comparisons to normative values were done for flexion, abduction, external rotation [25] and horizontal adduction [26] only. Thus, eighteen joint movements (ankle, knee, hip and trunk) were compared for both HSEBT and SEBT, with the addition of four shoulder joint movements for the HSEBT only.

Our clinical experience indicated that expressing test outcomes as areas provides a better feedback of results than composite scores. Therefore, both areas and composite scores were used in the analysis. Total area (A_{tot}) was calculated as the sum of the areas covered by the 8 triangles obtained in the horizontal reach measurements (HR_i (i = 1(A0), 2(R45), 3(R90), 4

(R135), 5(P180), 6(L135), 7(L90) and 8(L45)) (Eq 4). Additionally, anterior (A_{ant}) (Eq 5) and posterior areas (A_{post}) (Eq 6) were calculated in order to differentiate between anterior and posterior HSEBT reaches, respectively. Composite scores (CS) were also calculated since they have been used to quantify combinations of SEBT reaches [27]. Specifically, CS were calculated as the sum of all (CS_{tot}), anterior (CS_{ant}), and posterior reaches (CS_{post}) (Eqs 7–9).

$$A_{tot} = \Sigma \frac{1}{2} \cdot HR_{1-8} \cdot HR_{1-8} \cdot sin45^{\circ} \quad (4)$$

$$A_{ant} = \Sigma \frac{1}{2} \cdot HR_{1-3,7-8} \cdot HR_{1-3,7-8} \cdot sin45^{\circ} \quad (5)$$

$$A_{post} = \Sigma \frac{1}{2} \cdot HR_{3-7} \cdot HR_{3-7} \cdot sin45^{\circ} \quad (6)$$

$$CS_{tot} = \Sigma HR_{1-8} \quad (7)$$

$$CS_{ant} = \Sigma HR_{1,2,8} \quad (8)$$

$$CS_{post} = \Sigma HR_{4-6} \quad (9)$$

In order to determine similarities of movement strategies between direction specific HSEBT and SEBT reaches, shared movement synergies were quantified as the number of common joint movements (maximum 12) and defined as: strong (>8), moderate (5 to 8) and weak (<5).

Descriptive statistics (mean and standard deviation (SD)) were calculated in Excel for Mac OS 10.10.5 (Apple Inc., Cupertino, CA, USA), version 14.4.8 (Microsoft Corp., Redmond, WA, USA). All other statistical tests were done using IBM SPSS version 21.0 (IBM, Armonk, NY, USA). Normality of the data was assessed using Shapiro Wilk´s test ($p<0.05$). Outliers were determined and removed from the analysis [28]. The relationship between HSEBT and SEBT areas, composite score and were estimated using linear regression analysis. Interpretation of correlation coefficients was done according to the guidelines of Portney and Watkins [29]. To determine whether the differences between $\theta_{maxHSEBT}$ and $\theta_{maxSEBT}$ were different, two-sided paired t-tests (level of confidence $\alpha>95\%$) were used. Effect size was calculated using Cohen´s *d* (<0.2 = small; 0.2 to 0.5 = medium; >0.8 = large effect).

Results

Test results for all HSEBT and SEBT reaches are presented in Figs 2, 3 and 4.

Total area (A_{tot}) and composite score (CS_{tot}) correlations ranged from .393 to .606, with statistical significance for the right foot only (Table 1). Both A_{ant} and CS_{ant} have higher correlations (.531 to .823) than A_{post} and CS_{post} (.269 to .406) (Table 1 and Fig 5). Anterior reaches, both on the left and right foot, had moderate to good correlations ranging from r = .515 to .572 and r = .707 and .822, respectively. None of the posterior reaches were significantly correlated (Figs 2 and 3). Anterior hand reach to posterior foot reach (A and CS) was significantly correlated (.534 to .698), while posterior hand reaches to anterior foot reaches (A and CS) was significantly correlated for the right foot only (.469 and .480) (Table 1). Variable correlations were observed for the lateral (-.182 to .510) and rotational reaches (.402 to .696).

A detailed description of elicited joint movements of both the HSEBT and the SEBT with reach specific comparisons is presented in Table 2. HSEBT anterior reaches resulted in ankle dorsiflexion (19.4–29.7˚), knee flexion (81.6–101.7˚), hip flexion (98.8–103.3˚) and trunk

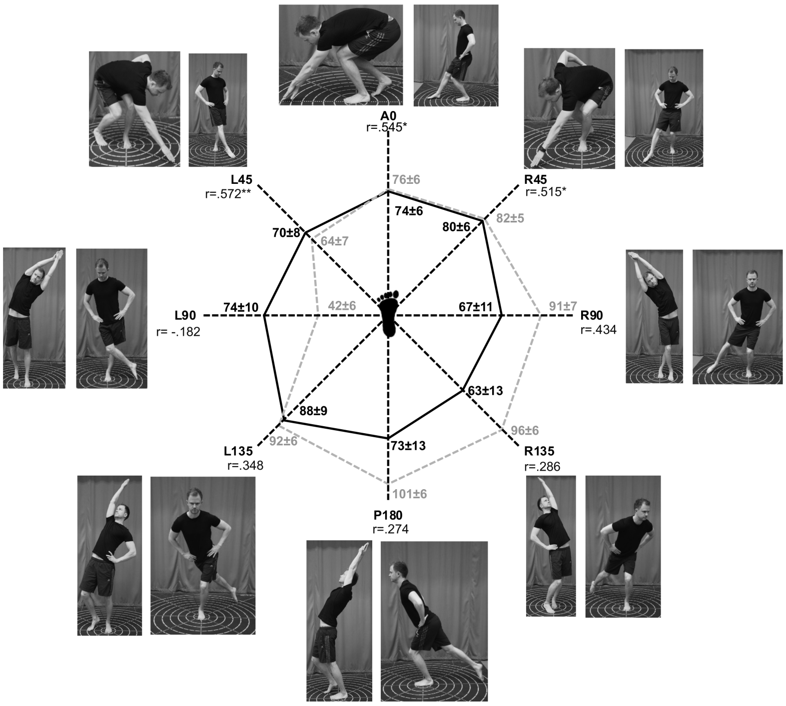

Fig 2. Horizontal reaches HSEBT and SEBT left leg. Visual representations of the execution of the horizontal reaches (photographs) and mean (±SD) reach distances (cm) observed for all tests in the center graphs for HSEBT (black) and SEBT (grey). Correlation coefficients (r) are shown for each direction ($^{*}p<0.05$ and $^{**}p<0.01$).

https://doi.org/10.1371/journal.pone.0196813.g002

flexion (51.2–58.8°), while posterior reaches elicited ankle dorsiflexion (19.7–24.5°), knee flexion (18.0–28.8°), hip extension (17.4–29.5°) and trunk extension (28.5–36.2°). HSEBT lateral reaches targeted different frontal plane movements where the L90 reach generated ankle inversion (7.5±4.5°), knee abduction (2.1±3.7°), hip abduction (16.9±6.3°) and ipsilateral trunk flexion (38.2±7.0°), whereas the R90 reach elicited ankle eversion (18.2±3.3°), knee adduction (2.7 ±3.0°), hip adduction (27.6±6.4°) and contralateral trunk flexion (38.8±5.8°). HSEBT rotational reaches targeted different transverse plane movements where the LROT reach induced ankle adduction (15.1±5.2°), knee internal rotation (15.1±3.7°), hip internal rotation (33.2 ±3.8°), whereas the RROT reach elicited ankle abduction (13.4±3.6°), knee external rotation (23.8±5.4°), hip external rotation (29.5±5.4°) and contralateral trunk rotation (33.7±4.5°). Shoulder extension, adduction, internal rotation and horizontal abduction are not reported since no test targeted these movements specifically and the observed $\theta_{maxHSEBT}$ were small.

Shared joint movement synergies ranged from weak to strong (4 to 10 out of 12). Anterior and posterior reaches induced shared movement synergies of 8-10/12 and 6-8/12, respectively. Whereas, lateral and rotational reaches demonstrated shared movement synergies of 4-9/12 and 8-10/12, respectively.

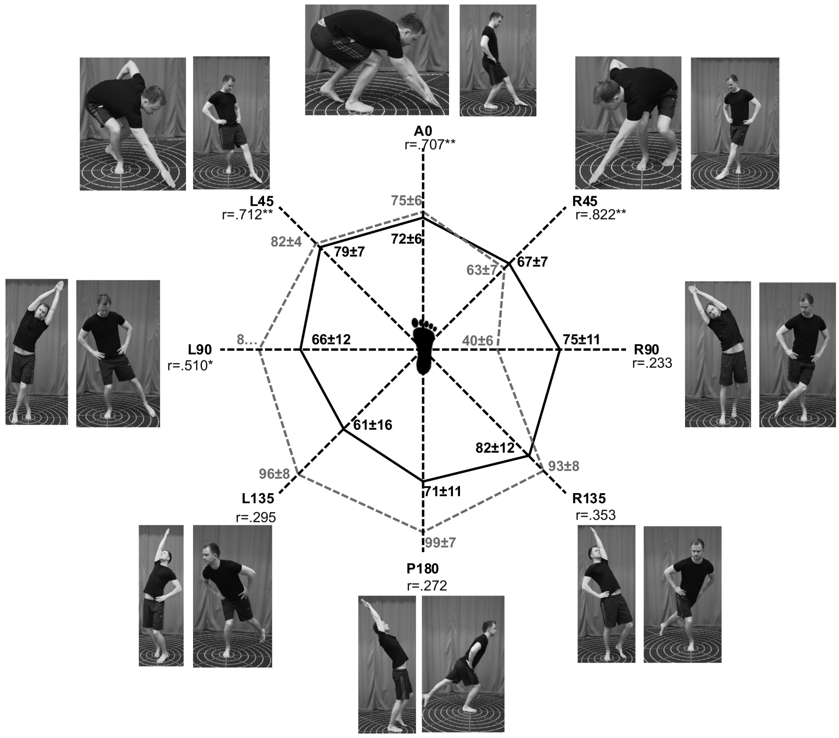

Fig 3. Horizontal reaches HSEBT and SEBT right leg. Visual representations of the execution of the horizontal reaches (photographs) and mean (±SD) reach distances (cm) observed for all tests in the center graphs for HSEBT (black) and SEBT (grey). Correlation coefficients (r) are shown for each direction (*p<0.05 and **p<0.01).

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The identified $\theta_{maxHSEBT}$ exhibited greater values than $\theta_{maxSEBT}$ for all joint movements, except for ankle dorsiflexion, plantarflexion and knee extension (Table 3). Joint movements with greater $\theta_{maxHSEBT}$ values were significantly greater than $\theta_{maxSEBT}$ for all comparisons, except for hip external rotation (t(34) = -0.51, p = .61, *d* = .09), with effect sizes ranging from medium to large (*d* = .39–5.21). The greater $\theta_{maxSEBT}$ values were significant for all comparisons with effect sizes ranging from medium to large (*d* = .45–1.39). Comparisons of $\theta_{maxHSEBT}$ and $\theta_{maxSEBT}$ to normative ROM values revealed that 8/22 and 3/18 joint movements, respectively, were within normative ROM values.

Discussion

The current study established that the HSEBT provides additional information about dynamic postural control and functional mobility. However, there seems to exist a relationship since total scores (A_{tot} and CS_{tot}) have demonstrated fair to moderate correlations. Nevertheless, large reach specific differences were noted. Anterior HSEBT reaches are closer related to both anterior and posterior SEBT reaches, which can be partially explained by stronger shared

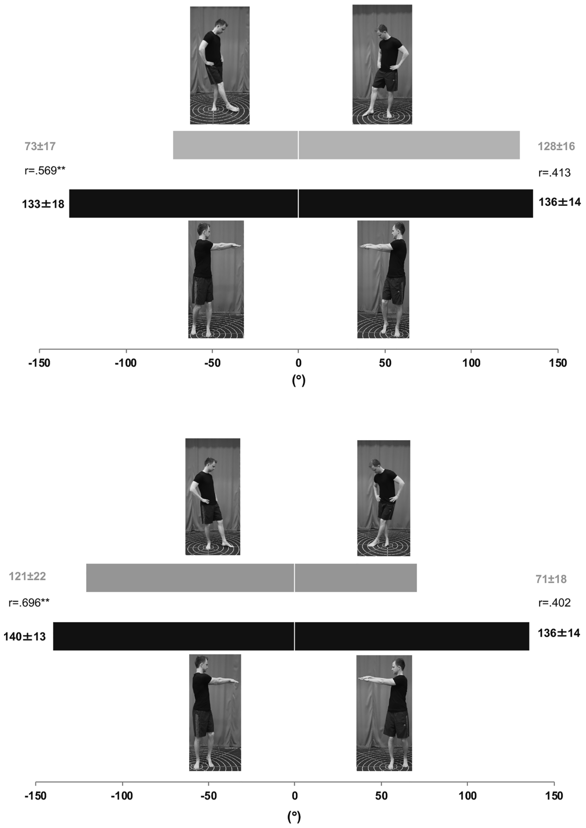

Fig 4. Rotational reaches HSEBT and SEBT. Visual representation of the execution of the rotational reaches (photographs) for both left (top) and right leg (bottom) with mean (± SD) reach excursion (°) observed for all tests in the horizontal bar graphs for both HSEBT (black) and SEBT (grey). Correlation coefficients (r) are shown for each direction (*$p<0.05$ and **$p<0.01$).

https://doi.org/10.1371/journal.pone.0196813.g004

movement synergies. Posterior and lateral HSEBT reaches demonstrated weaker relationships to their SEBT counterparts, indicating that these tests measure different aspects of dynamic postural control. Overall, the HSEBT elicited greater joint movements ($\theta_{maxHSEBT}$) than the SEBT ($\theta_{maxSEBT}$). In addition, 8/22 $\theta_{maxHSEBT}$ were within normative ROM values, while $\theta_{max-SEBT}$ had only 3/18 joint movements within normative ROM values. These findings may justify the application of the HSEBT as a useful clinical tool in the assessment of functional mobility.

Dynamic postural control

HSEBT is able to measure different aspects of dynamic postural control in comparison to the SEBT. The strength of the shared movement synergies could explain some of the differences

Table 1. Area and composite score comparisons between HSEBT and SEBT.

	Left foot		Right foot	
Comparisons	**r**	**R^2**	**r**	**R^2**
A_{tot}	.393.	.154	.602**	.362
A_{ant}	.531*	.282	.780**	.608
A_{post}	.269	.072	.406	.165
HSEBT A_{ant} and SEBT A_{post}	.534*	.285	.698**	.487
HSEBT A_{post} and SEBT A_{ant}	.227	.052	.480*	.230
CS_{tot}	.414	.171	.606**	.367
CS_{ant}	.605**	.366	.823**	.677
CS_{post}	.341	.116	.344	.118
HSEBT CS_{ant} and SEBT CS_{post}	.536*	.287	.608**	.370
HSEBT CS_{post} and SEBT CS_{ant}	.261	.068	.469*	.220

A_{tot}, Total area; A_{ant}, Anterior area; A_{post}, Posterior area; CS_{tot}, Total composite score; CS_{ant}, Anterior composite score; CS_{post}, Posterior composite score.

* $p<0.05$

** $p<0.01$

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observed. The lateral reach with a weak movement synergy (4/12) had little to no correlations, while the lateral reach with a strong movement synergy (9/12) had fair to moderate correlations. Furthermore, posterior reaches had moderate shared movement synergies (6-8/12) and fair correlations, while rotational and anterior reaches with moderate to strong shared movement synergies (8-10/12) had fair to good correlations (Table 2, Figs 2 and 3). Since anterior HSEBT (A0, R45 and L45) and posterior SEBT (P180, L135 and R135) reaches also had strong shared movement synergies (8-11/12, obtained from Table 2) and joint movements of a more similar magnitude, especially hip joint (Table 2), an anterior HSEBT to posterior SEBT CS comparison should not influence the moderate to good anterior CS correlations. However, correlation coefficients all decreased for these comparisons (Table 1). Thus, it appears that a shared movement synergy is only one of the plausible explanations for the variable correlations between the reaches. Specific joint movements of a shared movement synergy, as observed in the ankle, may have a greater influence considering that dorsiflexion was found to predict anterior SEBT reach performance [14, 30]. However, the influence of dorsiflexion on anterior HSEBT reach performance has not been established. Another reason for the differences in the correlations between reaches may lie in the similarity of balance boundary conditions. This could explain why the anterior HSEBT and SEBT CS comparisons had stronger correlations than the anterior HSEBT and posterior SEBT CS comparisons. Future studies utilizing center of pressure analysis should investigate this hypothesis. In addition, the influence of vision could also have influenced the anterior and posterior comparisons, since visual feedback of the reaching target was available for anterior, but not for posterior reaches. Composite scores of right foot anterior reaches and the R45 reach had good correlations, while the remaining comparisons yielded none to moderate correlations. This suggests that the HSEBT is able to measure some different aspects of dynamic postural control as compared to the SEBT.

Functional mobility

The multi-joint movements observed for the different maximum hand reaches are organized to meet the task requirements and to overcome internal constraints. These internal constraints include not only postural and balance control strategies, but also individual joint movement

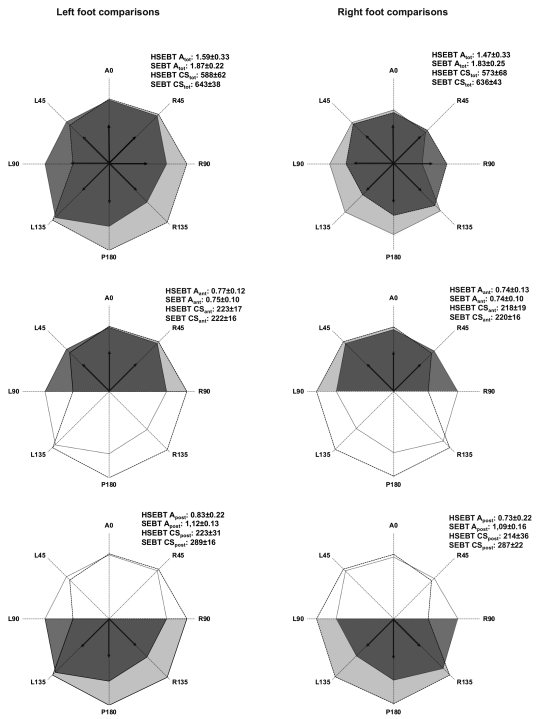

Fig 5. Area and composite score comparisons of HSEBT and SEBT. Visual representation of total (top row), anterior (middle row) and posterior (bottom row) comparisons of area (A_{tot}, A_{ant}, A_{post}) and composite score (CS_{tot}, CS_{ant}, CS_{post}). Color coding of area in the center graphs is defined as follows: dark (shared area HSEBT and SEBT), medium (unique HSEBT area) and light grey (unique SEBT area). Arrows represent the horizontal reaches included in CS_{tot}.

https://doi.org/10.1371/journal.pone.0196813.g005

capacities. Thus, reach measurements provide information of how the body is able to organize and utilize joint excursions in a more ecological way. The HSEBT is therefore an appropriate measure of functional mobility since it is the result of joint movement combinations of the lower extremity, trunk and shoulder.

The data presented here provide not only a reference for functional mobility (Figs 2 and 3), but also reference values of joint movements (θ) and their combinations elicited for all HSEBT reaches in a young and healthy male population (Table 2). Our kinematic data, as well as data from other studies [10–14], demonstrated that hand reaches resulted in more joint movements than foot reaches alone. Furthermore, $\theta_{maxHSEBT}$ were significantly greater for trunk, hip (except external rotation), knee, ankle, and upper extremity than $\theta_{maxSEBT}$ (Tables 2 and 3). In addition, $\theta_{maxHSEBT}$ were also more consistent within normative ROM values (8/22 joint movements) in comparison $\theta_{maxSEBT}$ (3/18 joint movements). The greater joint movements observed with the HSEBT ($\theta_{maxHSEBT}$) might be due to the larger base of support in the HSEBT, whereby decreasing the balance and postural control demand. Thus, the HSEBT appears to be a good alternative to quantify functional mobility.

Table 2. Kinematic comparisons HSEBT and SEBT.

Test	Direction	Plane of motion	Ankle θ (°)	Knee θ (°)	Hip θ (°)	Trunk θ (°)	Shoulder θ (°)	Movement synergy
HSEBT	A0	Sag	**DF:26.2±4.5**	**Flex:101.7 ±16.0**[a]	**Flex: 103.3 ±19.8**	**Flex: 58.8±9.7**[a]	Flex: 112.9±11.3	8/12
		Front	**Ev:12.9±5.8**	**Add: 13.2±7.8**	Abd: 1.0±7.4	Ipsi lat flex: 4.1±4.5		
		Trans	**Abd:6.1±3.2**	**IR: 12.9±10.4**	ER: 1.7±5.5	Ipsi rot: 0.9±3.6		
SEBT	A0	Sag	**DF: 31.0±4.7**	**Flex: 64.9±11.2**	**Flex: 24.4 ±16.0**	**Flex: 3.5±16.5**		
		Front	**Ev: 4.3±3.2**	**Add: 3.8±6.4**	Add: 16.6±5.1	Contra lat flex: 2.0 ±10.4		
		Trans	**Abd: 7.4±2.0**	**IR: 3.2±4.5**	IR: 11.6±5.4	Contra rot: 0.6±3.2		
HSEBT	R45	Sag	**DF: 29.7±5.7**[a]	**Flex: 88.3±32.3**	**Flex: 108.2 ±7.9**[a]	**Flex: 51.2±6.8**	Flex: 117.7±11.5	10/12
		Front	**Ev: 12.5±4.7**	**Add: 17.2±6.5**[a]	Abd: 16.0±6.3	**Contra lat flex: 1.2 ±6.3**		
		Trans	**Abd: 11.5 ±4.0**	**ER: 6.1±7.9**	ER: 2.2±8.0	**Contra rot: 15.2±5.3**	ER: 36.4±18.8; Hor add: 63.7 ±9.2	
SEBT	R45	Sag	**DF: 32.5±5.1**[b]	**Flex: 63.9±16.1**	**Flex: 18.3 ±20.1**	**Flex: 8.9±13.9**		
		Front	**Ev: 2.5±3.8**	**Add: 3.2±6.2**	Add:10.3±6.7	**Contra lat flex: 0.3 ±13.4**		
		Trans	**Abd: 10.8 ±2.4**[b]	**ER: 1.5±6.2**	IR: 9.1±8.9	**Contra rot: 0.2±5.5**		
HSEBT	R90	Sag	**DF: 8.6±7.5**	**Flex: 6.6±13.6**	Ext: 0.5±11.2	Ext: 14.0±10.8	Flex: 127.9±14.6	9/12
		Front	**Ev: 18.2±3.3**[a]	Add: 2.7±3.0	**Add: 27.6±6.4**[a]	**Contra lat flex: 38.8 ±5.8**[a]	Abd:127.9±13.8*	
		Trans	**Abd: 2.1±3.4**	**IR: 1.6±3.8**	**IR: 2.1±6.0**	**Contra rot: 9.3±5.8**		
SEBT	R90	Sag	**DF: 30.2±5.5**	**Flex: 77.1 ±12.6**[b]	Flex: 65.2±14.0	Flex: 10.9±13.1		
		Front	**Ev: 1.5±4.1**	Abd: 1.5±6.5	**Add: 0.8±7.1**	**Contra lat flex: 0.9 ±12.9**		
		Trans	**Abd: 9.0±2.8**	**IR: 3.1±7.7**	**IR: 18.4±4.8**	**Contra rot: 1.1±5.4**		
HSEBT	R135	Sag	**DF: 19.7±5.7**	**Flex: 18.0±10.6**	Ext: 17.4±5.2	Ext: 28.5±9.7	Flex: 149.8±14.4	7/12
		Front	**Ev: 5.2±4.7**	Abd: 1.7±2.2	**Add: 12.1±5.2**	**Contra lat flex: 20.6 ±8.0**		
		Trans	Add: 0.6±4.5	**IR: 8.0±3.8**	**IR: 10.4±6.0**	Ipsi rot: 2.3±8.0	ER: 49.2±23.5	
SEBT	R135	Sag	**DF: 25.0±6.5**	**Flex: 70.4±14.4**	Flex: 84.3±10.3	Flex: 17.0±13.7[b]		
		Front	**Ev: 3.7±3.4**	Add: 3.4±7.0	**Add: 9.4±7.1**	**Contra lat flex: 0.5 ±16.2**		
		Trans	Abd: 4.6±4.3	**IR: 4.1±6.0**	**IR: 10.1±6.1**	Contra rot: 0.9±5.7		
HSEBT	P180	Sag	**DF: 24.5±6.4**	**Flex: 21.1±10.2**	Ext: 28.3±5.6	Ext: 36.2±7.2[a]	Flex: 144.3±13.0	8/12
		Front	**Ev: 0.8±2.6**	Abd: 1.6±2.4	**Add: 2.9±3.8**	**Contra lat flex: 3.2 ±3.6**		
		Trans	**Abd: 4.7±2.4**	IR: 2.8±3.4	**ER: 3.7±4.0**	**Contra rot: 1.8±2.8**		
SEBT	P180	Sag	**DF: 27.4±5.1**	**Flex: 75.2±10.7**	Flex: 93.8±8.8[a]	Flex: 18.1±13.8		
		Front	**Ev: 5.3±2.6**	Add: 11.0±6.8[b]	**Add: 13.6±4.2**	**Contra lat flex: 0.6 ±15.8**		
		Trans	**Abd: 7.9±2.4**	ER: 1.1±6.8	**ER: 4.4±6.9**	**Contra rot: 1.8±3.7**		
HSEBT	L135	Sag	**DF: 23.0±8.0**	**Flex: 28.8±14.0**	Ext: 29.5±6.8[a]	Ext: 33.9±9.7	Flex: 150.6±15.8[a]	6/12
		Front	Inv: 5.3±4.4	Abd: 1.8±3.4	Abd: 10.4±6.0	Ipsi lat flex: 18.3±7.9		
		Trans	**Abd: 10.2 ±3.0**	**ER: 5.2±5.1**	**ER: 20.4±5.5**	**Contra rot: 2.7±8.9**	ER: 50.3±25.5[a]	

(*Continued*)

Table 2. (Continued)

Test	Direction	Plane of motion	Ankle θ (°)	Knee θ (°)	Hip θ (°)	Trunk θ (°)	Shoulder θ (°)	Movement synergy
SEBT	L135	Sag	**DF: 25.4±5.5**	**Flex: 58.0±13.4**	Flex: 78.9±14.6	Flex: 10.8±11.5		
		Front	Ev: 7.4±3.5	Add: 15.8±7.4	Add: 12.1±4.7	Contra lat flex: 0.6 ±18.0		
		Trans	**Abd: 7.9±2.7**	**ER: 7.8±4.9**	**ER: 17.0±7.5**	**Contra rot: 0.7±4.2**		
HSEBT	L90	Sag	DF: 9.1±9.3	Flex: 21.6±24.5	**Flex: 8.3±23.8**	**Ext: 14.8±12.9**	Flex: 130.6±12.6	4/12
		Front	Inv: 7.5±4.5[a]	Abd: 2.1±3.7	Abd: 16.9±6.3[a]	Ipsi lat flex: 38.2±7.0[a]	Abd: 129.5±13.8[a]	
		Trans	**Abd: 0.0±3.4**	IR: 0.1±4.9	**IR: 4.3±13.5**	Ipsi rot: 11.2±9.0		
SEBT	L90	Sag	PF: 2.3±3.4[b]	Ext: 8.7±4.8[b]	**Flex: 12.9 ±10.1**	**Ext: 5.1±8.7[b]**		
		Front	Ev: 12.2±3.8[b]	Add: 2.3±1.3	Add: 23.3±7.4[b]	Contra lat flex: 0.5±9.2		
		Trans	**Abd: 0.1±3.6**	ER: 6.0±5.2	**IR: 2.0±5.8**	Contra rot: 1.3±5.2		
HSEBT	L45	Sag	**DF: 19.4±8.2**	**Flex: 81.6±20.6**	**Flex: 98.8±8.2**	**Flex: 57.4±10.2**	Flex: 107.6±11.4	10/12
		Front	Inv: 1.1±5.0	**Add: 6.2±6.9**	**Add: 15.2±5.5**	Ipsi lat flex: 11.0±6.7		
		Trans	**Add: 8.2±4.9**	**IR: 12.4±6.7**	**IR: 2.1±6.0**	**Ipsi rot: 15.3±4.4**	ER: 30.4±12.7; Hor Add: 76.2 ±14.7	
SEBT	L45	Sag	**DF: 18.6±7.6**	**Flex: 39.7±17.7**	**Flex: 14.8 ±13.9**	**Flex: 3.1±10.7**		
		Front	Ev: 4.3±4.1	**Add: 2.4±6.1**	**Add: 18.4±4.5**	Contra lat flex: 4.2±9.8		
		Trans	**Add: 5.3±3.3**	**IR: 9.7±3.4**	**IR: 12.5±5.0**	**Ipsi rot: 1.3±5.6**		
HSEBT	LROT	Sag	DF: 0.7±5.2[a]	**Flex: 12.8±7.5**	**Flex: 10.8±5.8**	**Ext: 6.8±7.9**		10/12
		Front	Inv: 5.9±5.0	**Abd: 5.5±1.9[a]**	**Add: 9.8±3.7**	**Ipsi lat flex: 7.4±5.6**		
		Trans	**Add: 15.1 ±5.2[a]**	**IR: 15.1±3.7[a]**	**IR: 26.9±5.1[a]**	**Ipsi rot: 33.2±3.8[a]**	Hor Add: 132.8±10.7[a]	
SEBT	LROT	Sag	PF: 0.1±5.4	**Flex: 7.2±11.1**	**Flex: 9.2±8.4[b]**	**Ext: 3.6±7.0**		
		Front	Ev: 0.9±5.7[b]	**Abd: 2.6±2.4[b]**	**Add: 12.9±6.1**	**Ipsi lat flex: 5.9±7.2[b]**		
		Trans	**Add: 10.6 ±4.7[b]**	**IR: 13.7±4.8[b]**	**IR: 19.2±5.4[b]**	**Ipsi rot: 7.6±6.9[b]**		
HSEBT	RROT	Sag	**DF: 10.0±5.5**	**Flex: 6.7±11.7[a]**	Ext: 2.6±6.0	Ext: 2.8±8.2		8/12
		Front	**Ev: 5.9±3.4**	**Add: 3.8±2.6**	Add: 0.7±5.1	Contra lat flex: 7.2±5.5		
		Trans	**Abd: 13.4 ±3.6[a]**	**ER: 23.8±5.4[a]**	**ER: 29.5±5.4[a]**	**Contra rot: 33.7±4.5[a]**	Hor Add: 134.2±13.9[a]	
SEBT	RROT	Sag	**DF: 14.9±6.7**	**Flex: 23.4±13.9**	Flex: 12.4±8.0	Flex: 2.4±7.3		
		Front	**Ev: 4.2±4.4**	**Add: 6.2±3.9**	Abd: 5.9±7.7[b]	Ipsi lat flex: 2.0±6.3		
		Trans	**Abd: 9.1±2.9**	**ER: 16.5±5.2[b]**	**ER: 27.2±7.1[b]**	**Contra rot: 3.2±9.6**		

Shaded and white rows identify direction specific HSEBT and SEBT reach comparisons with bold font showing common joint movements

Sag, Sagittal plane; Front, Frontal plane; Trans, Transverse plane; DF, Dorsiflexion; PF, Plantarflexion; Ev, Eversion; Inv, Inversion; Abd, Abduction; Add, Adduction; Flex, Flexion; Ext, Extension; ER, External rotation; IR, Internal rotation; Ipsi, Ipsilateral; Contra, Contralateral; Lat flex, Lateral flexion; Rot, Rotation; Hor add, Horizontal adduction

[a] = maximum magnitude of specific joint movement elicited by HSEBT

[b] = maximum magnitude of specific joint movement elicited by SEBT

https://doi.org/10.1371/journal.pone.0196813.t002

The HSEBT quantifies functional mobility in the sagittal (A0 and P180), frontal (L90 and R90) and transverse planes (LROT and RROT). The plane specific capacity of these reaches is reflected by its ability to elicit one or more $\theta_{maxHSEBT}$ in their respective planes of motion. (Table 3). Since decreased ROM of specific joints have been found to impact joint movements elsewhere in the kinetic chain [31, 32], the HSEBT could be used to assess the influence of joint mobility limitations on functional mobility. One approach could be to measure multiple

Table 3. Maximum joint movements elicited by HSEBT and SEBT with comparisons to normative ROM.

Joint	Plane	Joint Movement	Reach	$\theta_{maxHSEBT}$ (°)	Reach	$\theta_{maxSEBT}$ (°)	t-test	Cohen´s *d*	Normative ROM	HSEBT comparison	SEBT comparison
Ankle	Sag	DF	R45	29.7±5.7	R45	32.5±5.1	t(38) = 5.95 p < .01	.95	26.1±6.5[e]	x	x
		PF	LROT	-0.7±5.2	L90	2.3±3.4	t(39) = 2.91, p < .01	.45	40.5±8.1[e]		
	Front	Ev	R90	18.2±3.3	L90	12.2±3.8	t(39) = -9.46, p < .01	1.50	21±5[e]	x	x
		Inv	L90	7.5±4.5	LROT	-0.9±5.7	t(38) = -8.00, p < .01	1.28	37±4.5[e]		
	Trans	Abd	RROT	13.4±3.6	R45	10.8±2.4	t(38) = -5.45, p < .01	.87	NR	NA	NA
		Add	LROT	15.1±5.2	LROT	10.6±4.7	t(38) = -5.57, p < .01	.89	NR	NA	NA
Knee	Sag	Flex	A0	101.7±7	R90	77.1±12.6	t(39) = -9.08, p < .01	1.44	141±5.3[e]		
		Ext	RROT	-6.7±11.7	L90	8.7±4.8	t(38) = 8.67, p < .01	1.39	2±3[e]	x	x
	Front	Abd	LROT	5.5±1.9	LROT	2.6±2.4	t(38) = -7.79, p < .01	1.25	NR	NA	NA
		Add	R45	17.2±6.5	P180	11.0±6.8	t(39) = 9.04, p < .01	1.43	NR	NA	NA
	Trans	IR	LROT	15.1±3.7	LROT	13.7±4.8	t(38) = 2.45, p = .019	0.39	20[f]		
		ER	RROT	23.8±5.4	RROT	16.5±5.2	t(37) = -9.73, p < .01	1.58	30[f]		
Hip	Sag	Flex	R45	108.2±7.9	P180	93.8±8.8	t(39) = -13.37, p < .01	2.11	121±6.4[e]	x	
		Ext	L135	29.5±6.8	LROT	-9.2±8.4	t(36) = 25.92, p < .01	4.26	12±5.4[e]	x	
	Front	Abd	L90	16.9±6.3	RROT	5.9±7.7	t(37) = 7.59, p < .01	1.23	41±6[e]		
		Add	R90	27.6±6.4	L90	23.3±7.4	t(38) = 2.95, p < .01	0.47	27±3.6[e]	x	
	Trans	IR	LROT	26.9±5.1	LROT	19.2±5.4	t(37) = 10.91, p < .01	1.77	44±4.3[e]		
		ER	RROT	29.5±5.4	RROT	27.2±7.1	t(34) = -0.51, p = .61	.09	44±4.8[e]		
Trunk	Sag	Flex	A0	58.8±9.7	R135	17.0±13.7	t(38) = -18.53, p < .01	2.97	60[f]		
		Ext	P180	36.2±7.2	L90	5.1±8.7	t(38) = -18.03, p < .01	2.88	45[f]		
	Front	Lat flex	L90 and R90	38.4±6.4[a]	LROT	5.9±7.2	t(38) = -29.43, p < .01	5.21	35[f]	x	
	Trans	Rot	LROT and RROT	33.4±4.2[b]	LROT	7.6±6.9	t(38) = -21.32, p < .01	3.41	38[f]		
Shoulder	Sag	Flex	L135	150.6±15.8	NA	NA			167±4.7[e]		
	Front	Abd	L90 and R90	128.7±12.8[c]	NA	NA			184±7[e]		
	Trans	ER	L135	50.3±25.5	NA	NA			104±8.5[e]		
		Hor Add	LROT and RROT	133.5±12.3[d]	NA	NA			130[f]	x	

Shaded and white rows identify joints and regions

Sag, Sagittal plane; Front, Frontal plane; Trans, Transverse plane; DF, Dorsiflexion; PF, Plantarflexion; Ev, Eversion; Inv, Inversion; Abd, Abduction; Add, Adduction; Flex, Flexion; Ext, Extension; ER, External rotation; IR, Internal rotation; Ipsi, Ipsilateral; Contra, Contralateral; Lat flex, Lateral flexion; Rot, Rotation; Hor add, Horizontal adduction; L, Left; R, Right; A0, Anterior reach; R45, Right anterolateral (45˚) reach; R90, Right lateral (90˚) reach; R135, Right posterolateral (135˚) reach; P180, Posterior (180˚) reach; L135, Left posterolateral (135˚) reach; L90, Left lateral (L90) reach; L45, Left anterolateral (45˚) reach; RROT, Right rotational reach; LROT, Left rotational reach; NA, Not applicable; NR, Not reported; x, within normative ROM.

[a] Average trunk lateral flexion L90 and R90 reach

[b] Average trunk rotation LROT and RROT reach

[c] Average shoulder abduction L90 and R90 reach

[d] Average shoulder horizontal adduction LROT and RROT reach

[e] Reference value from Greene and Heckman [25]

[f] Reference value from Magee [26]

https://doi.org/10.1371/journal.pone.0196813.t003

hand reaches to explore if specific joint mobility limitations could be identified. For example, anterior reaches (L45, A0 and R45) resulted in both common and different joint movements (Table 2). These flexion movement patterns, based on common ankle dorsiflexion, knee and hip flexion, elicit different frontal and transverse plane movements. The decrease in anterior reach values in L foot R45 compared to L45 suggests that sagittal plane joint movements of the lower extremity are influenced by frontal and transverse plane joint movements. More specifically, less dorsiflexion was observed with inversion and adduction (L45) than with eversion and abduction (R45) (Table 2). These findings are supported by the work of Tiberio and coworkers who showed that a pronated ankle yielded greater dorsiflexion [33]. Furthermore, L45 hand reach resulted in less hip flexion when compared to R45. This could be explained by the impact of both hip internal rotation and adduction (in the L45 reach) approaching positions of bony impingement as previously described in the literature [34]. In contrast, the hip external rotation and abduction associated of the R45 reach did not approach positions of bony impingement [34]. Thus, both L foot L45 and R foot R45 hand reaches can be used as a weight bearing version of a common clinical test for femoroacetabular impingement (FAI), which is currently done in supine with hip passively brought into flexion, adduction and internal rotation (FADIR).

Frontal and transverse plane trunk movements are opposite for the L45 and R45 reaches possibly having an influence on the reach results. However, these opposite movements are less than 50% of observed $\theta_{maxHSEBT}$ (Tables 2 and 3) suggesting that these trunk movements do not impact reach measurements significantly. Similar to the anterior reach analysis, posterior reaches or extension movement patterns based on a common hip extension, can be analyzed to determine the influence of frontal and transverse plane joint movements on extension.

The HSEBT and SEBT elicited 8 of 22 and 3 of 18 joint movements that were within normative ROM values, respectively. This is not surprising considering that joint ROM measurements are usually obtained using goniometry in positions that do not require neither strength nor neuromuscular control. Furthermore, the transfer of joint ROM to functional tasks has only limited significance [35]. Considering that the HSEBT elicited more and greater trunk, upper and lower extremity joint movements coupled into one functional unit [36], the HSEBT may also be a good assessment tool for functional mobility.

Clinical application

The HSEBT has the potential to have complementary and wider clinical application possibilities than the SEBT, which is primarily used in the assessment of the lower extremity function [27, 37–43]. Since the HSEBT integrates more and greater joint movements of the full kinetic chain, it might find clinical applications in e.g. low back pain (LBP), where the assessment of full-body movements has been reported as underexplored [21]. Furthermore, in patients with shoulder dysfunctions hand reaches can provide important clinical information since dynamic positioning of the scapula to stabilize the glenohumeral joint is dependent on the segmental coordination of the entire kinematic chain [20]. In addition, the HSEBT could be useful in fall risk management since falling occurs while reaching, leaning [44] and bending [45]. Currently, a single item hand reach test, the functional reach test [16], and the multi-directional reach test [18] are used to quantify limits of stability in populations at risk. However, these tests only include reaches at shoulder level, neither provoking overhead activities nor bending. Thus, the HSEBT might be an alternative tool in fall risk management. Furthermore, the HSEBT can be useful in the assessment of athletes participating in overhead sports such as throwing (baseball and European handball) and hitting (tennis and golf).

Conclusions

In comparison to the SEBT, the HSEBT measures different aspects of dynamic postural control, especially in the posterior and lateral reaches. Shared movement synergies could explain some of the observed relationships between both tests. Considering that the HSEBT elicit more and greater joint movements than the SEBT, and that there is no currently available functional mobility assessment tool, the HSEBT may also present a useful addition to the available test methods of functional mobility.

Acknowledgments

Ali Ghelem and Jessica Parnevik-Muth for assisting in the development of the HSEBT. Fredrik Sæland, Eirik Hammerseth Andreassen and Stavros Litsos for their help in the data acquisition. Olivier Seynnes and Jens Bojsen-Møller for valuable input during the preparation of the manuscript.

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Paper III

©Journal of Sports Science and Medicine (2019) **18**, 91-100
http://www.jssm.org

Research article

Functional Mobility and Dynamic Postural Control Predict Overhead Handball Throwing Performance in Elite Female Team Handball Players

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Abstract

The relationship between dynamic postural control, functional mobility and team handball throwing performance, velocity and accuracy, is largely unknown. The hand reach star excursion balance test (HSEBT) is a full kinetic chain assessment tool of these factors. Specifically, L135 and R135 (extension) reaches elicit joint movement combinations similar to the cocking and acceleration phase, while the L45 and R45 (flexion) reaches elicit joint movement combinations similar to the follow-through. The purpose of this study was to determine if specific HSEBT reach measures correlate with team handball throwing performance. Eleven elite female team handball players (21.7 ± 1.8 years; 71.3 ± 9.6 kg; 1.75 ± 0.07 m) executed selected HSEBT reaches before performing five valid step-up overhead throws (1x1m target) from which throwing velocity (motion capture) and accuracy (mean radial error) were quantified. Significant relationships between HSEBT measures and mean radial error, but not throwing velocity were established. Specifically, extension composite scores (L135+R135) for the dominant (150.7 ± 17.4cm) and non-dominant foot (148.1 ± 17.5 cm) were correlated with mean radial error ($p < 0.05$). Also, specific reaches on the dominant (L135: 87.4 ± 5.6 cm; R135: 63.4 ± 11.8 cm) and non-dominant (R135: 87.0 ± 6.1 cm) foot were correlated with throwing error ($p < 0.05$). The lack of significant findings to throwing velocity might be due to a ceiling effect of both L135 and R135 and of throwing velocity. We conclude that while there may be other reasons for handball players to train and test functional mobility and dynamic postural control as measured in the HSEBT, no beneficial effect on throwing performance should be expected in an elite group of handball players.

Key words: Ball games, ball velocity, throwing accuracy, dynamic postural control.

Introduction

In team handball, throwing performance is determined by both velocity and accuracy (Wagner et al., 2008). The combination of these two factors gives defenders and/or goalkeepers less time to parry the shot, thus increasing the likelihood of scoring (van Muijen et al., 1991). Throwing performance is the result of sequential muscle activation, torque generation, energy transfer, and a proximal to distal increase of joint angular velocities in the kinetic chain that starts in the lower extremities and progresses through the trunk into the upper extremities (Bartlett, 2000; Fradet et al., 2004; Herring and Chapman, 1992; Joris et al., 1985; Roach et al., 2013; van den Tillaar and Ettema, 2004; 2007; 2009b; Wagner et al., 2011; 2012; 2014). This sequential behaviour requires joint mobility for both angular acceleration and deceleration throughout the kinetic chain. In their study Roach and Lieberman reported that limiting proximal kinetic chain segmental mobility by bracing decreased joint power generation throughout the kinetic chain, angular velocities, elastic storage of energy at the shoulder, and throwing velocity (Roach and Lieberman, 2014). Furthermore, kinetic chain analyses of handball throwing found correlations between throwing velocity and maximum joint positions obtained during the cocking and acceleration phase (van den Tillaar and Ettema, 2007; Wagner et al., 2011).

Since full kinetic chain analysis of throwing performance is an impractical field method, joint mobility is commonly quantified using traditional goniometric measurements of range of motion (ROM). However, only few studies explored the influence of ROM measurements on throwing performance, and non-significant findings have been reported (Schwesig et al., 2016; van den Tillaar, 2016). Furthermore, ROM measurements have an uncertain capacity to predict injuries (Andersson et al., 2018; Clarsen et al., 2014). These findings might be due to some inherent limitations of the traditional measurements. Firstly, ROM measurements might not be representative of the actual maximum joint movements attained during the throw (van den Tillaar, 2016). Secondly, goniometric measures only provide information about uniplanar and unidirectional movements of specific joints, and do not provide information about their role in the kinetic chain. Thirdly, in the current literature assessing throwing performance, goniometric measures are only applied to upper extremity joint movements, even if maximum trunk and pelvic rotations have been reported to also be important determinants (Wagner et al., 2011). Finally, passive goniometric tests have low neuromuscular demands. In fact, to the knowledge of the authors no studies so far explored the influence of dynamic postural control on team handball throwing performance. The lack of measurements that target kinetic chain assessment of both mobility and dynamic postural control are in contrast to current practice in the female Norwegian national team, where testing and training that integrate lower extremity, trunk and shoulder movements are used for both mobility and dynamic postural control purposes. Considering that this is the most successful female handball team in the past two decades (Olympic games, World Championships and European Championships several gold, silver and bronze medals), it is interesting to observe that such assessments are lacking in the literature.

Received: 05 April 2018 / Accepted: 30 November 2018 / Published (online): 01 March 2019

Considering the aforementioned shortcomings, a study into the influence of mobility on throwing performance should include assessment of the full kinetic chain and impose greater neuromuscular demands. Thus, tests of functional mobility – i.e. the combination of range of motion (ROM) of multiple joints in ecological movements – might be an appropriate assessment strategy. The hand reach star excursion balance test (HSEBT) appears to be an appropriate test since the joint movements elicited by the different sub-tests (Eriksrud et al., 2018) are similar to those associated with overhead handball throwing (van den Tillaar and Ettema, 2007; Wagner et al., 2011). Other tests such as the star excursion balance tests (SEBT) (Gribble et al., 2012; Kang et al., 2015), upper quarter Y-balance test (UQYBT) (Gorman et al., 2012) and functional movement screen (FMS) (Butler et al., 2010; Cook et al., 2006) do not have this capacity.

Specifically, the HSEBT posterior overhead unilateral hand reach measurements quantify the ability to position the hand in space, which elicit hip, trunk and shoulder joint movements (Eriksrud et al., 2018) similar to those observed in the late cocking and acceleration phases of overhead throwing (van den Tillaar and Ettema, 2007; Wagner et al., 2011). Furthermore, the unilateral anterior diagonal hand reaches to floor level elicit combinations of hip, trunk and shoulder joint movements (Eriksrud et al., 2018) similar to those observed in the follow-through phase (van den Tillaar and Ettema, 2007; Wagner et al., 2011). In addition, the rotational reaches target transverse plane joint movements (Eriksrud et al., 2018) associated with the different phases of the throw (van den Tillaar and Ettema, 2007; Wagner et al., 2011).

Therefore, the purpose of this study was to determine the influence of functional mobility and dynamic postural control assessed through specific HSEBT reaches on team handball throwing performance. We hypothesized that specific HSEBT measures correlate with throwing accuracy or throwing velocity.

Methods

Participants

Thirteen Norwegian, international level, female handball players volunteered for the study, with eleven completing the entire protocol (age: 21.7 ± 1.8 years; weight: 71.3 ± 9.6 kg; height: 1.75 ± 0.07 m; wingspan: 1.74 ± 0.09 m). Debut in the elite division in Norway was 3.5±1.9 years prior to participation in the study, and at the time of the study two players were on the national team while four different players participated in European club competitions. Exclusion criteria were musculoskeletal or neurological dysfunction or injury in the past six months, inability to participate in normal handball and throwing activities, and pain or discomfort reported during testing. All tests were done in the afternoon and participants were instructed to eat and hydrate as they would do for a regular practice. The committee for medical and health research ethics in Norway (2014/2230) and the Norwegian Centre for Research Data (40934) had reviewed and approved the study. Measurements were carried out according to the principles described in the Declaration of Helsinki. All subjects were given written and verbal information about the experimental risks associated with the study and signed an informed consent form prior to participation. Testing was done mid to late season.

Experimental design

This was a descriptive and cross-sectional cohort study for comparison of HSEBT reaches with overhead throwing performance (ball velocity and accuracy). Specifically, HSEBT reaches that represent joint movements associated with the different phases of the overhead handball throw, cocking, acceleration and follow-through, were selected. The unilateral posterior overhead reaches (L135 and R135) were tested since hip, trunk and upper extremity joint movements and positions assumed in these reaches (Eriksrud et al., 2018) are similar to those observed in the cocking and acceleration phase in the same joints (van den Tillaar and Ettema, 2007; Wagner et al., 2011). Similarly, the unilateral anterior diagonal reaches to floor level (L45 and R45) were tested since hip, trunk and upper extremity joint movements and positions assumed in these reaches (Eriksrud et al., 2018) are similar to those observed in the follow-through phase in the same joints (van den Tillaar and Ettema, 2007; Wagner et al., 2011). Furthermore, Left (LROT) and right (RROT) rotational reaches were done to target the hip and trunk rotations associated with the three phases of the throw (van den Tillaar and Ettema, 2007; Wagner et al., 2011).

Anthropometric measurements and limb dominance

Prior to testing, body height and weight were obtained using a Seca model 217 stadiometer and a Seca flat scale (Seca GmbH. & Co. Hamburg, Germany). A standard tape measure was used to measure wingspan (tip of middle finger to middle finger with shoulder abducted to 90 degrees in standing), arm length (acromion to tip of middle finger with shoulder abducted to 90 degrees in standing) and leg length (greater trochanter to floor in standing). The dominant hand was defined as the throwing hand, while the dominant foot was defined as the pivot foot in the 8-meter throw with run-up.

Warm-up

All subjects performed a 15-minute standardized warm-up. The general warm-up (10 minutes) consisted of jogging, different shuffle runs, skipping and dynamic stretching focusing on full body movements in all three planes of motion. The handball-specific part (5 minutes) consisted of throwing at a large target (wall) with a gradual increase in velocity with the last 2-3 throws at maximum throwing velocity.

Throwing protocol

A throwing target was indicated on a high-jump mat (2 m x 3 m) placed vertically in front of a handball goal in order to protect lab equipment. Based on different protocols previously used in handball throwing studies (van den Tillaar and Ettema, 2003; Wagner et al., 2014) sports tape was used to define a +-shaped throwing target (1 m x 1 m). For right-handed subjects the target was placed 0.1 m below the crossbar at the right side of the goal's midline.

This was mirrored for the left-handed subjects (van den Tillaar and Ettema, 2003). An International Handball Federation standard size women's handball (Select AS, Glostrup, Denmark) was used for all throws. A three-step run-up throw from 8 m was used, since this throw is frequently used in team handball when throwing from the backcourt position (Wagner et al., 2012). All subjects were given the following instructions: "Throw the ball as hard as you can and hit the target" (van den Tillaar and Ettema, 2003). There was a one-minute rest period between throws. The subjects continued throwing until five valid throws (inside the target) were obtained.

Dynamic postural control and functional mobility

Dynamic postural control and functional mobility were assessed using the HSEBT, which has been reported to be valid and reliable (Eriksrud et al., 2017). The original HSEBT consists of 10 hand reaches on each foot (stance foot) with a toe-touch of the opposite foot. Reach direction definitions and procedures are described in detail elsewhere (Eriksrud et al., 2017), but are summarized here for clarity. HSEBT reaching directions are defined from the anatomical neutral position as follows: direction (i.e.: anterior (A); posterior (P)), side of body (left (L); right (R)), angle at 45° increments from anterior (0°) to posterior (180°) and movement (rotation (ROT)). Reaches along the 8 horizontal reach vectors (A0, R45, R90, R135, P180, L135, L90 and L45) are horizontal reaches (HR) and measured in centimeters (cm), while the two rotational reaches (LROT, RROT) are measured in degrees (°). Of the horizontal reaches, the diagonal reaches (L45, R45, L135, R135) were selected based on the similarity of elicited hip, trunk and shoulder joint movements and positions (Eriksrud et al., 2018) to the different phases of the throw (van den Tillaar and Ettema, 2007; Wagner et al., 2011) as described previously. Based on sagittal plane hip movements at maximum reach position, L45 and R45 are considered flexion while L135 and R135 are extension movement patterns. In addition, left (LROT) and right rotational reaches (RROT) were performed to target full body rotation. All HSEBT reaches were performed in the same order on a testing mat specifically designed to guide and perform measurements. Specifically, the testing mat identifies the eight horizontal reaching directions with imprinted marks at 2 cm intervals, and nine concentric circles (at 10 cm intervals) with marks at 5-degree intervals (Athletic Knowledge Nordic AB, Stockholm, Sweden). A plumb line (L135 and R135) and a stick (LROT and RROT) were used to project the position of the middle digit of the reaching hand(s) to the mat. Images of HSEBT tests and maximum reach positions are presented in Figure 1 and 2. Three to five practice trials were allowed, after which three valid reaches were recorded and the maximum value used for analysis. Trials were discarded if the procedures were not followed. Composite scores (CS) where calculated as the sum of horizontal reaches for the following: dominant foot (CS_{dom}), non-dominant foot ($CS_{non\text{-}dom}$), dominant foot flexion movement patterns (CS_{dom_flex}), non-dominant foot flexion movement pattern ($CS_{non\text{-}dom\_flex}$), dominant foot extension movement pattern (CS_{dom_ext}) and non-dominant foot extension movement pattern ($CS_{non\text{-}dom\_ext}$).

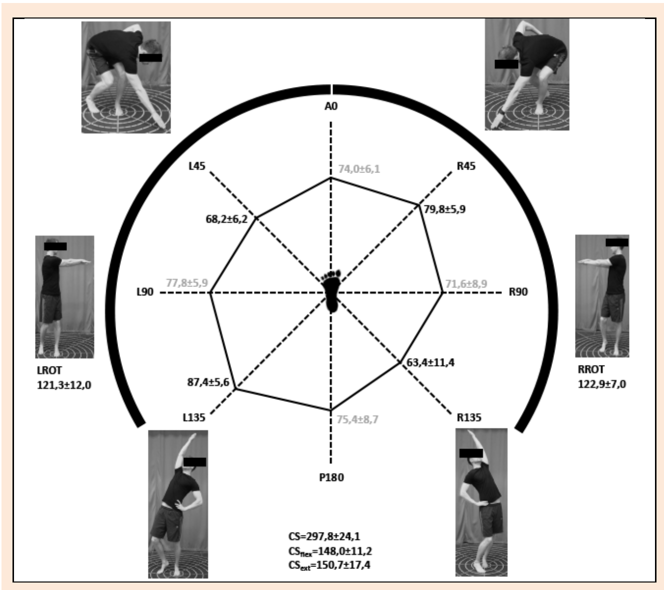

Figure 1. Horizontal and rotational reaches HSEBT dominant leg with accuracy comparisons. Visual representations of the execution of the horizontal and rotational reaches (photographs) on the left foot (9/11 subjects left foot dominant) with mean (±SD) reach distances (cm, °) for observed (black) and calculated (grey) HSEBT reaches and CS (sum of horizontal reaches), CS_{flex} (sum flexion movements patterns) and CS_{ext} (sum extension movement patterns) with their correlations (r, * $p < 0.05$)

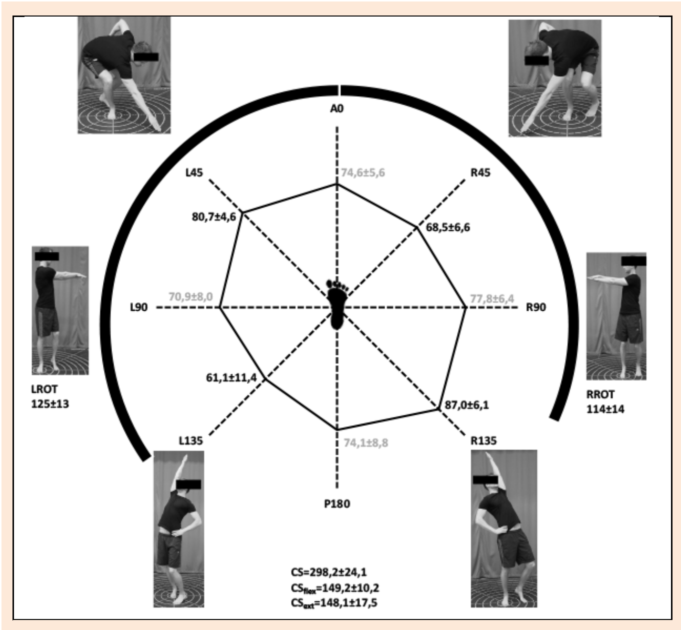

Figure 2. Horizontal and rotational reaches HSEBT non-dominant leg with accuracy comparisons. Visual representations of the execution of the horizontal and rotational reaches (photographs) on the left foot (2/11 subjects right foot non-dominant) with mean (±SD) reach distances (cm, °) for observed (black) and calculated (grey) HSEBT reaches and CS (sum of horizontal reaches), CS_{flex} (sum flexion movements patterns) and CS_{ext} (sum extension movement patterns) with their correlations (r, * $p < 0.05$)

Kinematic and video analysis

Five Oqus-4 cameras (Qualisys AB, Gothenburg, Sweden) were used to collect kinematic data (recorded at 480 Hz) from five reflective markers (20 mm ϕ) attached to the ball (two markers opposite each other to determine the center of the ball), throwing hand (head of the intermediate phalanx of the third digit) and pelvis (highest point left and right iliac crest). Marker data was filtered (2nd order Butterworth low pass filter with 15Hz cut-off frequency), then throwing velocity ($m \cdot s^{-1}$), was calculated as the average velocity between frames 3 and 8 after time (t_0) (frame of maximum acceleration between the marker on the third digit and the center of the ball (midpoint between the two ball markers), which increases abruptly at ball release (van den Tillaar and Ettema, 2007). Entry velocity ($m \cdot s^{-1}$) was defined as the maximum velocity of the midpoint between the two pelvic markers 3 and 100 ms prior to t_0. Both throwing and entry velocity were calculated for all throws using Matlab (Mathworks Inc, Natick MA, USA). Accuracy of all throws was calculated from video analysis using a video camera (Basler acA2000 – 165uc video camera (Baser AG, Ahrensburg, Germany)) placed 12 m away from the target at a height of 2 m. Mean radial error was used as the accuracy measurement and defined as the average of the absolute distance from the center of the ball to the center of the target (van den Tillaar and Ettema, 2003) using Dartfish (Dartfish, Fribourg, Switzerland). The number of throws used by each subject to reach five valid throws was recorded but only the valid throws were used for analysis.

Statistical analysis

Descriptive statistics (mean and standard deviation (SD)) were calculated in Excel for Mac OS 10.10.5 (Apple Inc., Cupertino, CA, USA), version 14.4.8 (Microsoft Corp., Redmond, WA, USA). All other statistical tests were done using IBM SPSS version 21.0 (IBM, Armonk, NY, USA). Normality of the data was assessed using the Shapiro-Wilk test ($p < 0.05$). Pearson correlation analysis (two-tailed) was done to determine the relationship between throwing velocity, accuracy, number of attempts and tests of dynamic postural control (cm, ° and CS). Linearity of the relationships between these variables were assessed using visual inspection of scatter plots. Outliers were determined and removed from the analysis based on adding or subtracting the interquartile range multiplied by 2.2 from the mean of measurements (Hoaglin and Iglewicz, 1987). Dynamic postural control tests are presented based on the dominant foot and hand respectively. Since 9 of 11 players were left foot dominant, left foot reach definitions were used for the presentation of the HSEBT results.

Results

The throwing performance of the participants was as follows: entry velocity (3.1 ± 0.5 $m \cdot s^{-1}$), throwing velocity (22.8 ± 1.9 $m \cdot s^{-1}$), accuracy (0.32 ± 0.09 m), and number of throws (8.8 ± 3.0) (average ± SD). Reach measurements and composite scores for the dominant and non-dominant foot are presented in Table 1 and Figure 1 and 2. All independent and dependent variables were normally distributed (Shapiro Wilk > 0.05). There was no throwing velocity and accuracy trade-off (r = 0.062, p = 0.856). No significant correlations between number of throws and throwing velocity (r = -0.267, p = 0.428) and accuracy and number of throws (r = 0.330, p = 0.322) were observed. No significant correlations between throwing velocity and individual HSEBT reaches or composite scores were observed (Table 1) with small coefficients of determination (R^2= 0.0004 to 0.11) (Figure 3). However, correlations between HSEBT composite scores and mean radial error were significant for the dominant (CS_{dom} r = 0.622, p < 0.05) and approached significance for the non-dominant foot ($CS_{non\text{-}dom}$ r = 0.584, p = 0.059). Significant correlations between mean radial error and extension movement pattern composite scores for both the dominant foot (CS_{dom_ext} r = 0.756, p < 0.05) and non-dominant foot ($CS_{non\text{-}dom\_ext}$ r = 0.656, p < 0.05) were observed (Table 1). Both the L135 (r = 0.725, p < 0.05) and R135 (r = 0.698, p < 0.05) reaches on the dominant foot and the R135 reach (r = 0.839, p < 0.05) on the non-dominant foot were significantly correlated with the mean radial throwing error. These significant findings corresponded with greater coefficients of determination ranging from 0.34 to 0.70 (Figure 4).

Table 1. Correlations HSEBT measurements and throwing performance.

Measurement		Measurement (mean±SD)	Throwing velocity	Mean radial error
Dominant	R45 (cm)	79.8 ± 5.9	.315 (p=.345)	.124 (p=.717)
	L45 (cm)	68.2 ± 6.2	.205 (p=.546)	.488 (p=.128)
	L135 (cm)	87.4 ± 5.6	.126 (p=.713)	.725 (p=.012)*
	R135 (cm)	63.4 ± 11.8	.275 (p=.413)	.698 (p=.017)*
	RROT (º)	122.9 ± 7.0	-.242 (p=.473)	.128 (p=.780)
	LROT (º)	121.3 ± 12.0	-.551 (p=.079)	.072 (p=.834)
	CS (cm)	297.8 ± 24.1	.326 (p=.328)	.622 (p=.041)*
	CS_{flex} (cm)	148.0 ± 11.2	.280 (p=.404)	.334 (p=.315)
	CS_{ext} (cm)	150.7 ± 17.4	.243 (p=.472)	.756 (p=.007)*
Non-dominant	R45 (cm)	68.5 ± 6.6	-.020 (p=.953)	.361 (p=.276)
	L45 (cm)	80.7 ± 4.6	.141 (p=.679)	.009 (p=.979)
	L135 (cm)	61.1 ± 11.4	.111 (p=.745)	.483 (p=.132)
	R135 (cm)	87.0 ± 6.1	-.062 (p=.856)	.839 (p=.001)*
	RROT (º)	114.1 ± 10.3	-.064 (p=.852)	-.075 (p=.826)
	LROT (º)	125.2 ± 10.1	-.393 (p=.232)	.226 (p=.503)
	CS (cm)	298.2 ± 24.1	.026 (p=.939)	.584 (p=.059)
	CS_{flex} (cm)	149.2 ± 10.2	.050 (p=.883)	.237 (p=.483)
	CS_{ext} (cm)	148.1 ± 17.5	.055 (p=.873)	.656 (p=.028)*

* p < 0.05. L=Left; R=Right; R45=Right anterolateral (45°) reach; R135=Right posterolateral (135°) reach; L135=Left posterolateral (135°) reach; L45=Left anterolateral (45°) reach; RROT=Right rotational reach; LROT=Left rotational reach

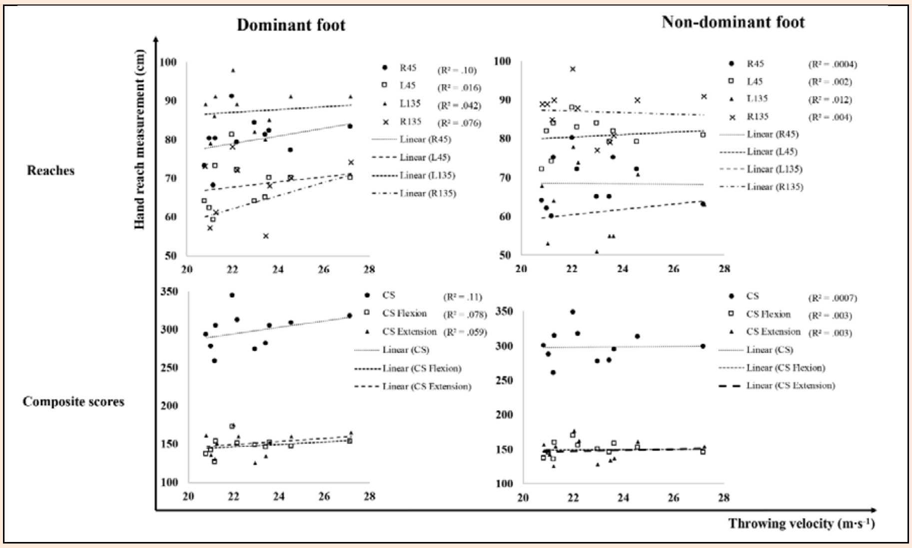

Figure 3. The relationship between hand reach measurements and throwing velocity shown for all subjects for specific hand reaches and composite scores (lines) for the dominant and non-dominant foot (columns). Specific reaches and composite scores identified by symbols with their respective coefficients of determination (R^2).

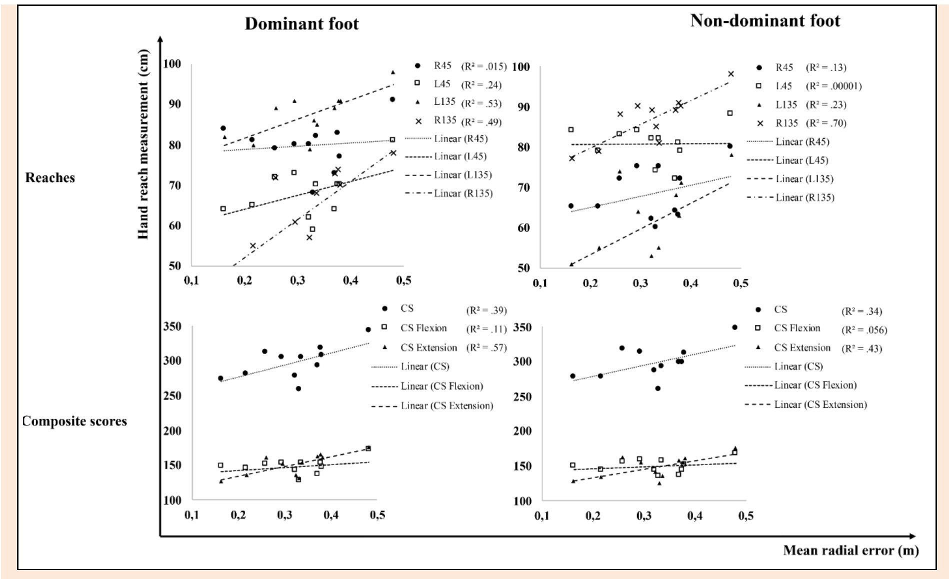

Figure 4. The relationship between hand reach measurements and throwing accuracy shown for all subjects for specific hand reaches and composite scores (lines) for the dominant and non-dominant foot (columns). Specific reaches and composite scores identified by symbols with their respective coefficients of determination (R^2).

Discussion

The current study could not confirm the hypothesized positive relationship between HSEBT reaches and throwing performance. Specifically, no correlations were found between HSEBT reaches and throwing velocity and HSEBT reaches correlated negatively with throwing accuracy (positive correlation with mean radial error). These results suggest that within the group of world-class players tested in the current study, increased dynamic joint mobility, as assessed through the HSEBT, is not a beneficial factor for throwing performance. Compared to other athletes that were tested so far (Eriksrud et al., 2017; 2018) the athletes in the current study showed unusually large reach distances. Therefore we speculate that a ceiling effect could explain that no correlation was found with throwing velocity, while the negative relationship with throwing accuracy might indicate that some of the players may have surpassed an optimum in joint mobility.

A secondary result of the current study was that there was neither a trade-off, nor a correlation between throwing velocity and throwing accuracy. This is a finding that agrees well with previous observations (Garcia et al., 2013; van den Tillaar and Ettema, 2003; 2006).

Throwing velocity

The throwing velocities measured in the current study are comparable to what has been reported elsewhere for elite female handball players (Granados et al., 2007; 2008; Vila et al., 2012). Tests of functional mobility and dynamic postural control, both HSEBT reaches and composite scores, did not correlate with throwing velocity. Hip extension, pelvic rotation, trunk rotation and extension are joint movements associated, on the one hand, with the approach, cocking and acceleration phase of the throw (van den Tillaar and Ettema, 2007; Wagner et al., 2011), and on the other hand, with the different posterior reaches (Eriksrud et al., 2018). Furthermore, Wagner and co-workers found that maximum trunk and pelvic rotation during the throw were correlated with throwing velocity (Wagner et al., 2011). Therefore it seemed plausible to expect a correlation between HSEBT results and throwing velocity. Our findings, however, did not support this assumption. Considering that all subjects were elite level handball players, they could all have had sufficient joint mobility to generate high throwing velocities (ceiling effect). In fact, comparisons of L135 and R135 reach measurements for both the dominant and non-dominant foot to available reference data showed that the handball players have reach measurements greater than established minimal detectable change (Eriksrud et al., 2017). However, such differences could not be observed for flexion and rotational movements patterns (Eriksrud et al., 2017). These comparisons might indicate that the players in the current study have sufficient functional mobility and dynamic postural control associated with the cocking and acceleration phase for the generation of high throwing velocities.

Based on current and previous findings, it appears that ROM, functional mobility and dynamic postural control measurements do not predict throwing velocity. Thus, mobility and dynamic postural control measurements should perhaps be analysed in combination with measures of other neuromuscular qualities to better understand the underlying factors influencing throwing velocity. Muscular strength and power are more studied than mobility and have been found to be significantly correlated with throwing velocity (Chelly et al., 2010; Cherif et al., 2016; Debanne and Laffaye, 2011; Fleck et al., 1992; Gorostiaga et al., 2005; Granados et al., 2007; Manchado et al., 2013; Marques et al., 2007). Specifically, power tests (kneeling medicine ball throw) and strength and power training (overhead medicine ball throwing) that target joint movements similar to those observed in the posterior overhead reaches (shoulder flexion, hip and trunk extension) have been found to be correlated with throwing velocity (Debanne and Laffaye, 2011; Hermassi et al., 2015).

Throwing accuracy

The throwing accuracy observed in the current study (0.32±0.09m) was comparable with previous findings (van den Tillaar and Ettema, 2003; 2006; Wagner et al., 2010; 2011; Zapartidis et al., 2007). Unlike throwing velocity, accuracy has not received the same attention in the literature. The effect of instructions (Garcia et al., 2013; van den Tillaar and Ettema, 2003; 2006), age and sex (Gromeier et al., 2017), fatigue (Nuno et al., 2016; Zapartidis et al., 2007), performance level (Rousanoglou et al., 2015; van den Tillaar and Ettema, 2006), temporal constraints (Rousanoglou et al., 2015), throwing techniques (Wagner et al., 2010) and laterality (van den Tillaar and Ettema, 2009a) on throwing accuracy have been explored. However, only two studies explored the influence of neuromuscular qualities, such as strength and power, on accuracy (Raeder et al., 2015; Zapartidis et al., 2007). Accuracy was found to decrease with fatigue, while shoulder strength and throwing velocity did not (Zapartidis et al., 2007), indicating that there is no relationship between shoulder strength and throwing accuracy. This finding was supported by Raeder et al. (2015), who reported medicine ball training improved strength, power, velocity, but not throwing accuracy. To the best of the authors´ knowledge no studies so far explored the influence of clinical tests of mobility or dynamic postural control on accuracy. In addition, mobility data available from kinematic studies, maximum joint positions obtained during the cocking and acceleration phase or magnitude of joint movements utilized during the throw, have been used to analyze throwing velocity (van den Tillaar and Ettema, 2007; Wagner et al., 2010; 2011) but not accuracy, with one exception (Urban et al., 2015). Urban and co-workers showed that decreased movement kinematics from stable to unstable throwing conditions lead to decreased throwing velocity with no influence on accuracy (Urban et al., 2015). However, the population studied had a much lower throwing velocity (16 m·s-1) than what was observed in the current study. Furthermore, the influence of mobility and dynamic postural control on accuracy in other comparable overhead and throwing sports has also received little attention. In baseball, static stretching did not influence accuracy (Haag et al., 2010), while better static balance in baseball (Marsh et al., 2004) and lacrosse (Marsh et al., 2010) improved accuracy (Marsh et al., 2010).

Considering the limited information available on the influence of dynamic postural control and functional mobility on throwing accuracy current findings provide valuable information on this important throwing performance factor. Our findings showed that greater posterior overhead hand reach measurements were correlated with lower throwing accuracy. One speculative interpretation of this finding might be that posterior overhead reaches quantify proprioceptive and balance demands associated with throwing. Measures of proprioception are correlated with successful basketball free-throw performance (Sevrez and Bourdin, 2015), but not throwing accuracy in baseball (Freeston et al., 2015) or lacrosse (Marsh et al., 2010). Based on their findings, Freeston et al. (2015), argued that proprioception of the entire kinetic chain should be assessed since proprioception of the shoulder joint in isolation did not correlate with throwing accuracy. If proprioception is measured by the HSEBT and more accurate throwers have better proprioception, then lower posterior overhead reach measurements represent better, or a better use of proprioceptive information. It might be that some players stopped at a maximum reach position at a lower reach measurement based on proprioceptive input from different joints or at a safer margin to limits of stability. Newton established that hand reaches have directional specific limits of stability (Newton, 2001) whereby it might be that more accurate throwers control these limits of stability in the posterior directions with a greater margin safety for stability purposes.

Limitations

One limitation – or strength, depending on the viewpoint – of the current study is the high performance level of the recruited handball players. Generalization of the findings in the current study beyond an international level female team handball population should be done cautiously. Exploration of how different performance levels, age and sex influence the relationship between HSEBT measurements and throwing performance seems warranted.

Clinical perspective

Full kinetic chain testing of functional mobility and dynamic postural control using the HSEBT might have different applications in team handball beyond assessment of throwing performance. Shoulder problems are one of the injury areas with the greatest impact on participation in team handball (Clarsen et al., 2014). Isolated tests of shoulder mobility have a variable capacity to predict shoulder injuries (Andersson et al., 2018; Clarsen et al., 2014). The HSEBT may offer important clinical information by addressing full kinetic chain movement tasks. Specifically, dynamic positioning of the scapula to stabilize the glenohumeral joint is dependent on segmental coordination of the entire kinematic chain (Kibler and Sciascia, 2016), which could be addressed by the HSEBT.

Conclusion

Overhead team handball throwing velocity and accuracy in elite female players were not beneficially influenced by functional mobility and dynamic postural control as measured by the HSEBT. There may be other reasons why elite handball players may want to train and test functional mobility and dynamic postural control utilizing the kinetic chain as in the HSEBT, particularly with regard to injury prevention; however, the current study suggests that no beneficial effect on throwing performance should be expected in an elite population.

Acknowledgements
In accordance with Journal of Sports Science and Medicine policy and our ethical obligation as researchers, we report that the first author is a co-founder of Athletic Knowledge AB (Stockholm, Sweden), which commercially distributes a testing mat for the star excursion balance test (SEBT) and HSEBT. The researchers received no funding or support that could have influenced the outcomes of the study. All experiments conducted complied with Norwegian laws and regulations.

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Key points

- This study is the first to explore the influence of dynamic postural and functional mobility on team handball throwing performance.
- Dynamic postural control and functional mobility as measured by the HSEBT did not positively affect throwing performance in an elite female population.
- Neither a trade-off nor a correlation between throwing velocity and accuracy were observed.
- The influence of different performance levels, age and sex on the relationship between HSEBT measurements and throwing performance should be explored.

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Paper IV

Influence of Anthropometry, Age, Sex and Activity Level on the Hand Reach Star Excursion Balance Test

Running title: Factors Influencing HSEBT reach performance

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Keywords: **Mobility, Postural Control, Testing, Instrument Development, Normalization**

Abstract

The influence of anthropometric measurements, age, sex and activity level have been found to influence tests of dynamic postural control such as the star excursion balance test (SEBT). The hand reach star excursion balance test (HSEBT) measures different aspects of dynamic postural control. The purpose of the present study was to explore the influence of these factors on the HSEBT. A convenience sample of 223 subjects performed four horizontal (L45, R45, L135 and R135) and two rotational (LROT and RROT) reaches. The influence of anthropometric measurements (height, arm length, leg length and wingspan) on reach measurements were assessed using stepwise multiple linear regression. Influence of age (young: <20 years; adult: >20 years), sex (male; female) and activity level (athletes; recreational) on reach measurements were analyzed using independent samples t-test ($p<.05$) and interpreted using effect size (Cohens *d*) and established values of minimal detectable change (MDC). Wingspan explained a significant portion of the variance of only R45 (34.6%) and L45 (11.7%) reach measurements and normalized (percentage of wingspan). A medium effect of age, sex and activity level was observed for normalized L45 and R45 reaches (d= .50 to .72). Group differences greater than MDC values and a medium effect for age (d= .55) and activity level (d= .75) were observed for the R135 reach. L45 and R45 reaches should be normalized to wingspan, but not the other reaches. Between individual or group comparisons should consider age, activity level and sex as potential covariates.

1 Introduction

The hand reach star excursion balance test (HSEBT) has proven to be a valid and reliable measurement tool for dynamic postural control (Eriksrud et al., 2017). The hand reaches performed on each foot capture different aspects of dynamic postural control as compared to the well-established star excursion balance test (SEBT) (Eriksrud et al., 2018). Furthermore, it measures functional mobility, i.e. the combined utilization of the ranges of motion (ROMs) of multiple joints for the accomplishment of activities of daily living and athletic performance in an ecological manner. In comparison to the SEBT the HSEBT elicits greater lower extremity and trunk movements with additional hip (extension) and upper extremity joint movements. Specifically, when compared to conventional ROM data, 8 of 22 joint movements were within these normative ranges (Eriksrud et al., 2018).

Currently, other hand reach tests such as the functional reach test (FR) (Duncan et al., 1990), standing lateral reach (Brauer et al., 1999), multidirectional reach test (Newton, 2001) and upper quarter Y balance test (Gorman et al., 2012a) are used to assess mobility and dynamic postural control. However, these tests are reaches in the horizontal plane that elicit small trunk and lower extremity joint movements (Duncan et al., 1990; Brauer et al., 1999; Newton, 2001), or are performed in positions non-specific to standing (i.e. planked position) (Gorman et al., 2012a). Since many actions in sports and activities of daily living are based on hand interactions with the environment (e.g. pushing, pulling, reaching, throwing) the HSEBT represents an alternative assessment offering better specificity in relation to such tasks (Eriksrud et al., 2018).

Patients with low back pain (LBP) have an altered lumbopelvofemoral rhythm (Laird et al., 2014) commonly assessed in standing flexion movements. However, lower extremity position, width and angulation, influence this rhythm with implications on postural stability (Zhou et al., 2016). Changes in stance not only influence base of support (BOS) but also lower extremity joint movements associated with the flexion task. The HSEBT can assess the lumbopelvofemoral rhythm not only in different flexion movements, but also in extension, lateral flexion and rotational movement patterns in a standardized manner. It may provide a better measurement tool to document such a rhythm, for example, in patients with LBP.

The HSEBT also appears to be a good addition to the assessment tools used for the evaluation of risk of falling, considering that falling often occurs while reaching, leaning (Nachreiner et al., 2007) or bending (Duckham et al., 2013). The functional reach test (FR), a single item hand reach test, has been reported to predict risk of falling (Scott et al., 2007). However, falls occur in multiple directions and it might be important to assess different directions to gain information about more multifaceted boundary conditions. In fact, Newton established that horizontal reaches in the anterior-posterior and medial-lateral direction quantify different limits of stability (Newton, 2001). The HSEBT therefore represents a promising addition to the assessment tools in fall risk management considering the high similarity of some of its tests with the movements already established as risk factors.

Shoulder dysfunction and injuries are common in throwing sports (Clarsen et al., 2014). Energy contribution and transfer through the kinetic chain to the shoulder have been described (Roach and Lieberman, 2014). For example, an increased leg drive in the tennis serve has been found to be associated with smaller shoulder and elbow torques while achieving the same serve speeds (Elliott et al., 2003), thus, potentially decreasing shoulder and elbow injury risks. Furthermore, restricting mobility of the torso by bracing resulted in a significant reduction in joint power generation throughout the kinetic chain, elastic storage of energy at the shoulder, and throwing velocity (Roach and Lieberman, 2014). Considering the importance of the full kinetic chain to shoulder function, the HSEBT may be a good alternative measure for shoulder function and dysfunction.

In the comparable SEBT, outcomes are known to be influenced by anthropometry, age, activity level and sex. Specifically, leg length was the anthropometric measurement found to explain a significant portion of the variance in the SEBT reaches (range R^2: .02 to .23). Therefore, SEBT was normalized to this anthropometric variable (Gribble and Hertel, 2003). Physical activities influence SEBT measures, specifically, between differences between sports have been observed (Bressel et al., 2007) with equivocal findings between athletes and recreational active individuals (Thorpe and Ebersole, 2008; Sabin et al., 2010; Ambegaonkar et al., 2013). The SEBT measures are also affected by sex, however there is a controversy with respect to the direction of the relationship. Sex has been found to have an equivocal effect on SEBT reach measures with no effect (Gribble and Hertel, 2003), greater reach measures in males than females (Gorman et al., 2012b; Holden et al., 2016), and vice versa

(Gribble et al., 2009; Holden et al., 2016). In adolescents and young adults, the SEBT reaches were found to increase with age (Holden et al., 2016; Gonzalo-Skok et al., 2017; McCann et al., 2017).

Therefore, the purpose of the current study was to determine the influence of anthropometric measurements, age, sex and activity level on HSEBT reaches and to provide reference values for future comparisons.

2 Methods

2.1 Participants

A convenience sample of 223 subjects participated in the study. Recreational active (n=57) and handball players (n=12) were recruited. We defined recreationally active as individuals that regularly participated in physical activity for at least 30 minutes four times a week. Furthermore, 154 athletes competing at the Youth Olympic Games (YOG) were recruited.

2.2 Testers and environment

Participation was voluntary and subjects were tested in different environments. The recreational active and the throwing athletes gave written informed consent prior to being tested by two experienced testers in the biomechanics laboratory of the university. The YOG athletes were evaluated at the Learn & Share area at the YOG Winter Games 2016 by four additional experienced testers (trainers and physical therapists). As a part of this experience the athletes had the opportunity compare their HSEBT reach measurements to anonymous data from World and Olympic champions in their respective sport. The following anonymous data were obtained and stored electronically: number as an identifier without any key, anthropometry (number, height, leg length, wing span and arm length), sex, sport and year of birth. Information about the study was shown on a computer screen in English. Based on the recommendation of the International Olympic Committee this information was also available in writing in the following languages: Norwegian, Chinese, English, French, Japanese, German, Korean and Russian. Then informed consent was obtained by checking a box on the computer screen. These procedures were discussed and formulated with lawyers from the Norwegian Sports Federation, and the study was approved and authorized by the Norwegian Data Protection agency and the Regional Committees for Medical and Health Research Ethics. The study was conducted according to the Declaration of Helsinki.

2.3 Anthropometric measurements

Height was obtained using a Seca model 217 stadiometer (Seca GmbH. & Co. Hamburg. Germany). Leg length was measured from the greater trochanter to the floor of one leg, arm length was measured from acromion to middle digit with shoulder abducted to 90° of one arm, and wingspan from middle digit to middle digit with both shoulders abducted to 90°. All measures were done with a standard tape measure (centimeter (cm)).

2.4 Testing procedures

Subjects were tested on a subset (six) of the ten hand reaches that make up the HSEBT (Eriksrud et al., 2017; Eriksrud et al., 2018). For clarity, HSEBT testing procedures are summarized here. The HSEBT reaches are defined from the anatomical position where the anterior (A0) and posterior (P180) reaches divide the body into left (L) and right (R) halves. Each half is then divided into reaches at 45-degree increments (R45, R90, R135, L135, L90 and R45). Of these eight reaches the R45, R135, L135 and L45 were tested on each foot. All of these are unilateral hand reaches and the hand selected to perform the reach was based on crossing midline (line connecting the A0 and P180 reach direction) with the opposite hand placed on the hip. Reach measurements were obtained on a mat with imprinted reaching directions with marks at two cm intervals and nine concentric circles at 10 cm intervals with the outer circle (90 cm radius) marked at 10-degree intervals (Athletic Knowledge Nordic AB, Stockholm, Sweden). The foot tested (stance foot) was placed in the center of the mat while the other foot (support foot) was placed (toe touch) at a 135-degree angle relative to the reaching direction between the 20 and 30 cm concentric circle. Maximum reach measurements from the center of the testing mat to the most distal point of the middle digit was then obtained. Specifically, position of the middle digit on the testing mat (light touch and no support) (R45 and L45), and from a plumb line projecting the position of the middle digit to the testing mat (R135 and L135) were obtained. Based on sagittal plane hip joint movements at maximum reach position, the R45 and L45 are considered flexion while the R135 and the L135 are considered extension movements. In addition, both left and right rotational reaches (LROT and RROT) were measured. For the rotational reaches the stance foot is placed in the middle of the testing mat with the support foot positioned parallel between the 20 and 30 cm concentric circle and allowed to rotate in the direction of the reach. Rotational reaches are bilateral hand reaches with the middle digits on top of each other. Maximum reach position was projected onto the concentric circles and quantified as the difference from A0 (0 degrees). Pictures of maximum reach positions standing on the right foot is presented in Figure 1. For all reaches, subjects were instructed to reach or rotate as far as possible at their own rate and then return to the starting position while maintaining balance. A minimum of three practice trials were given for each test to ensure that the test was understood, after which the maximum reach of three valid test trials were recorded for analysis.

Insert Figure 1 about here

2.5 Statistical analysis

Descriptive statistics (mean and standard deviation (SD)) of participant characteristics (anthropometric measurements and age) and reach measurements (R45, R135, L135, R135, LROT and RROT) shown in Figure 1 were calculated using Excel for Mac OS 10.10.5 (Apple Inc., Cupertino, CA, USA), version 14.4.8 (Microsoft Corp., Redmond, WA, USA). Mirrored reach test measurements on the left and right foot were compared using paired samples t-test. Side differences were interpreted based on effect size (Cohen's *d*) as follows: trivial<0.2; small 0.2 to 0.5; medium 0.5 to 0.8; large >0.8 (Cohen, 1988), and minimal detectable change (MDC) from test-retest reliability (Eriksrud et al., 2017).

The influence of anthropometric measures (height, wingspan, arm length, leg length and trunk), age, sex and activity level (athletes; recreational) on HSEBT measurements was determined using multiple regression analysis (IBM SPSS, v 21.0, IBM, Armonk, NY, USA). Measurements for the same tests on the left and right foot (e.g. left foot R45 reach and right foot L45 reach) were averaged. Linearity was assessed by visual inspection of scatter plots of studentized residuals and predicted values. Multicollinearity was assessed using variable inflation factor (VIF) with a cutoff of >10. Independences of residuals were analyzed using Durbin-Watson statistics with cutoff values <1 and >3. Homoscedasticity was assessed by visual inspection of the scatter plots of the standardized predicted values of the model and the standardized residuals. Normality of residuals was determined by visual inspection the histograms of standardized residuals and probability-probability plots. Casewise diagnostics were set to three standard deviations to determine if 1% or less of the subjects had standardized residuals outside this distribution. Specifically, a random sample, 75% of participants, were used to generate the initial model using forward stepwise regression based on a statistical significance (t-test). The model was then validated on the remaining 25% of the participants using forced entry. The validation model was then compared to the initial model based on change of R^2 values, and independent variables that significantly contributed ($p<.05$) to the model were retained. Pearson correlation coefficients of the retained variables to their respective HSEBT reaches were then calculated. The criterion for normalization of HSEBT reaches to anthropometric measures was based on significant correlation coefficients and R^2 values or changes greater than the coefficient of variation (CV) of the respective reach (Eriksrud et al., 2017).

Independent samples t-tests were then used to explore significant differences between age groups (young:<20 years; adult: >20 years), sex (M; F) and activity level (recreational; athletes). Homogeneity of variance was assessed using Levene´s test and normal distribution was assessed using Shapiro Wilks´s test. In the presence a significant Shapiro Wilk´s the test z-scores of both skewness and kurtosis were calculated to explore the necessity for data transformation. Effect size was calculated using Cohen´s *d* and interpreted as described above (Cohen, 1988). Outliers were removed based the criteria described by Hoaglin and Iglewics (Hoaglin and Iglewicz, 1987).

3 Results

Mean values of all variables measured of both athletic (sorted by sport) and recreational populations are provided in Table 1. Table 2 presents mean values for age, anthropometric measures and HSEBT reach measurements organized by groups (sex, age and activity level). In addition, significance of group differences, effect sizes and established MDC values are presented (Table 2). The male group was older than the female group (d=.83) with greater anthropometric measures (range d=0.94 to 1.51). The adult group also had greater anthropometric measures than the young group (range d=0.56 to 1.17). Recreational active were older than athletes (d=2.00) with greater anthropometric measures (range d=0.64 to 1.26). Females, young participants and athletes demonstrated significantly greater normalized L45 and R45 reach measurements ($p\leq.001$) with medium effect sizes. Trivial effects were observed for the non-normalized comparisons for these reaches with one exception: males had greater R45 reach measurements than females (small effect) with a group difference greater than MDC values. Small to medium effects for sex, activity level and age were observed for the R135 reach. Specifically, the athletic group had reach measurements greater than MDC values, while the observed difference between the young and the adult group (7.6 cm) is within the range of MDC values. The athlete group had significantly greater L135 reach measurements than the recreational group (small effect). The observed group difference (4.1 cm) is within the range of MDC values. Trivial to small effects were observed for age, sex and activity level on rotational reach measurements (Table 2).

Insert Table 1 and 2 about here

3.1 Regression analysis

Multicollinearity (VIF ranged from 1.000 to 4.152) was not observed. Homogeneity of variance was observed, with residuals being independent (Durbin-Watson ranged from 1.699 to 2.397). Wingspan explained 34.6 and 11.7% of the variance in the R45 and L45 reach measurements, respectively. Leg length explained 2.7% of the L135 reach (Table 3). No anthropometric variable could explain a significant portion of the variance in the R135, LROT and RROT reaches. Based on the aforementioned criteria, only the L45 and R45 measurements were normalized to wingspan and expressed as a percentage of wingspan. In R45 and L45 reaches, sex and leg length had a non-significant contribution in the validation model (Appendix 1). In addition, activity level and age explained 3.3 and 6.5%% of the L135 and R135 reaches respectively (Table 3).

Insert Table 3 about here

4 Discussion

4.1 Influence of anthropometry

Anthropometric measures influence HSEBT reach measurements differently, therefore reach specific normalization should be used. Flexion movement patterns yielded expected results: wingspan explained 11.7 and 34.6% of the variation in reach measurements. In addition, normalizing flexion movement patterns to wingspan resulted in significant differences for all groups (age, sex and activity level). However, extension movement patterns unexpectedly were not influenced by any of the anthropometric measures. Leg length did explain 2.7% of the variation in the R135 reach measurement. However, this is less than the previously established CV (Eriksrud et al., 2017). In addition, leg length did not significantly correlate with the R135 reach measurement, suggesting normalization to leg length is not needed. As expected, the rotational reaches do not require normalization. The reach specific considerations for HSEBT normalization differ from the normalization procedures proposed by Gribble and co-workers for the SEBT (Gribble and Hertel, 2003). In their study leg length was found to have greater coefficients of determination than height to SEBT reaches (.02 to .23), with significant correlations in 6 of 8 SEBT reach measurements (Gribble and Hertel, 2003). Although lateral and posterolateral reaches were not significantly correlated with leg length, all SEBT reaches are normalized to this measure and since then widely applied (Gribble et al., 2012). In fact, leg length explained 4% of the variance of the posterolateral reach measurement (Gribble and Hertel, 2003), which is less than the CV for test-retest reliability (4.4%) (Plisky et al., 2006). The normalization of HSEBT measurements to anthropometric variables which explain variation beyond error, as done in the current study, appears to be a more appropriate procedure.

4.2 Influence of age

There appears to be an effect of age on HSEBT reach measurements. Specifically, the young group has greater measurements in three of six reaches. Medium effects of age were observed for the normalized L45 and R45 reaches, as well as for the R135 reach. However, the group difference observed for the R135 reach (7.6 cm) is within the range of MDC values (Table 2). In their study Eriksrud and co-workers recommend 7 cm as an MDC for extension movement patterns based on calculations and clinical experience (Eriksrud et al., 2017). It is important to note that the MDC values in this study were calculated based on a 95% confidence interval, which is more conservative and generate greater values than the 90% confidence interval commonly used (Haley and Fragala-Pinkham, 2006). Consequently, we interpreted from our findings that the young participants had greater R135 reach measurements. The combination of significant group differences, effect sizes and comparison to established MDC values (R135) allows for a more robust interpretation of our findings. However, age did not explain a significant portion of the variation of any of the reach measurements in the regression analysis. Thus, it appears that age should be considered cautiously when performing between individual or group comparisons for the normalized L45 and R45 as well as for the R135 reach.

These findings contradict the influence of age on other measures of dynamic postural control such as the SEBT, where reach measurements increase with age (Holden et al., 2016; Gonzalo-Skok et al., 2017; McCann et al., 2017). However, these findings are based on young populations. Older basketball players (16 years) had increased SEBT measurements in some directions when compared to younger players (14 years) (Gonzalo-Skok et al., 2017). In a similar age group Holden and co-workers reported that 13-year-olds increased all SEBT reaches tested over a 24-month period

(Holden et al., 2016), while McCann and co-workers reported that older (20 years) had greater SEBT reach measures than younger (15 years) football players (McCann et al., 2017). However, only one study reported effect sizes (Gonzalo-Skok et al., 2017), and these studies did not compare group differences to recommended MDC values (5-7cm; 6-8% of leg length) (Munro and Herrington, 2010). Comparisons to these MDC values would change the interpretation of findings in the aforementioned studies. Older basketball players would still have greater SEBT reaches (Gonzalo-Skok et al., 2017) whereas older football players would not (McCann et al., 2017) in comparison to their younger counterparts. In addition, the observed increase in SEBT reaches over a 24-month period would only apply to the posterolateral reach (Holden et al., 2016). In the current study we calculated not only if group differences were significant, but also effect sizes before determining if group differences were greater than MDC values. This is a more robust analysis in comparison to what has been done for the SEBT, and allows us to be more certain about the effect of age on HSEBT reaches.

4.3 Influence activity level

Athletes have greater HSEBT reach measurements than recreationally active for three of six reaches. These reaches are the same as for the age group comparisons: normalized L45 and R45 reaches as well as the R135 reach. These group comparisons had medium effects, and the group difference for the R135 reach was greater than MDC values. Furthermore, activity level explained 3.3 and 6.5% of the variance of the L135 and R135 reaches. However, these values are less than most of the observed CV´s for these reaches (5.2 to 14.6%) (Eriksrud et al., 2017). In addition, the observed influence of activity level on these HSEBT reaches are influenced by age, since the athlete group was significantly younger than the recreational group (large effect) (Table 2). Based on these findings, activity level should be considered when performing between individual or group comparisons for the normalized L45 and R45 as well as the R135 reach.

The influence of activity level on SEBT reaches has been found to be equivocal. Specifically, female modern dancers have better reach performance in some, but not all reach directions, in comparison to active non-dancers (Ambegaonkar et al., 2013). In a study comparing basketball players Sabin and co-workers found that active controls had greater SEBT reach measurements than basketball players (Sabin et al., 2010). Thorpe and co-workers found that female soccer players (NCAA division 1) had greater SEBT reach measurements than their recreationally active counterparts (Thorpe and Ebersole, 2008). In addition, there are SEBT reach differences between athletes participating in different sports. Specifically, soccer players have greater SEBT reaches than basketball players, while there is no difference between gymnasts and soccer players (Bressel et al., 2007). However, these studies neither report effect sizes nor compare to MDC values as advocated by Munro and co-workers (Munro and Herrington, 2010). Comparing group differences to MDC values in the aforementioned studies influence interpretation of findings. Specifically, dancers would not have demonstrated greater SEBT reaches than non-dancers (Ambegaonkar et al., 2013), and basketball players would only have lower SEBT measurements in the anterior direction, and not in the medial and posterior (Sabin et al., 2010). Furthermore, soccer players would still have greater anterior and posterior reaches than their active controls (Thorpe and Ebersole, 2008). Overall, these findings indicate that there might not only be activity but also sports specific adaptations of dynamic postural as measured by the SEBT. In the current study it was not possible to determine sport specific adaptations due to the small sample sizes of the different sports included (Table 1), but the influence of activity level (athletic vs. recreational participation) could be analyzed. Since we calculated effect sizes and compared the group difference to established MDC values (R135), the inference that activity level leads to greater L45, R45 and R135 measurements is justified. However, some caution should be applied to the interpretation of these findings considering the that the athletic population was significantly younger (large effect), and that a smaller percentage of the reach measurement variance (3.3 to 6.5%) of only the L135 and R135 reaches could be explained by activity level.

4.4 Influence of sex

Females had significantly greater HSEBT reach measurements for normalized L45 and R45 reaches with a medium effect. These findings could be influenced by the female group being younger than the male group (*d*=0.83) since younger participants have greater normalized L45 and R45 reach measurements as discussed previously. It is interesting to note that males have significantly greater absolute R45 reach measurements with a small effect and a group difference less than MDC values. Normalization to wingspan changes this relationship completely with females having greater measurements (*d*=0.64). These findings might be due to males having a greater wingspan (10.9 cm; *d*=1.51), and that the R45 reach is where wingspan accounts for the greatest variation of the measurement (34.6%). Thus, females are better able to combine different joint movements to maximize R45 reach measurements despite having unfavorable anthropometrics.

Similar to our findings physically active females have been found to have greater SEBT reach measures than their male counterparts (Gribble et al., 2009). However, in their study Gribble and co-workers found no influence of sex on normalized SEBT reach measurements, and males having greater absolute SEBT reach measurements (Gribble and Hertel, 2003). Contrary to our findings, others have found males (Sabin et al., 2010) and athletic males (Gorman et al., 2012b) to have greater SEBT measures than their female counterparts. In the aforementioned studies neither effect sizes were reported nor were group differences compared to MDC values (Munro and Herrington, 2010). The group differences presented by Gribble and co-workers (Gribble and Hertel, 2003) are less than the established MDC values except for the posterior reach, while the group differences presented by Gribble and co-workers in their later study (Gribble et al., 2009) were all lower than established MDC values (visual interpretation from graphs). The values presented by Gorman and co-workers cannot be compared to MDC values since it is impossible to extract them from the graphs presented (Gorman et al., 2012b). Thus, it appears that sex has a small influence on SEBT reach measurements. Since sex had a medium effect and explained 4.2 and 8.9% of the variance of the R45 and L45 reach measurements respectively, greater than most CV´s for R45 and L45 reaches (3.0 to 5.2%) (Eriksrud et al., 2017), it appears that sex influence these HSEBT reaches. However, sex was not found to have a significant contribution to the validation model for the R45 and L45 reaches. Thus, the interpretation of sex influencing these reaches should be done cautiously.

4.5 Outlook, clinical implications and limitations

The current study established that HSEBT flexion movement patterns should be normalized to wingspan. However, wingspan explains only 34.6 and 11.7% of the variation in R45 and L45 reach measurements respectively. This leaves a large percentage of the variance to be determined by other factors. To date the HSEBT has been proven to be reliable and valid (Eriksrud et al., 2017) and measuring different aspects of dynamic postural control than the SEBT (Eriksrud et al., 2018). SEBT reaches have been found to reflect different neuromuscular functions such as proprioception (Belley et al., 2016), lower extremity strength (Hubbard et al., 2007; Crossley et al., 2011; Norris and Trudelle-Jackson, 2011), muscular power (Booysen et al., 2015) and balance (Hubbard et al., 2007). A better understanding of the influence of neuromuscular functions on HSEBT reach measurements should be explored.

The current study has shown that age, sex and activity level influence HSEBT measurements and consequently should be considered when performing between individual and group comparisons. The age groups compared in the current study were teenagers (age 17.1± .6) and young adults (age 24.3±3.4). To better understand the influence of age on the HSEBT, larger age ranges (>10 years) should be tested with measurements organized in age groups, as done for ROM data (Bell and Hoshizaki, 1981). This will allow for the development of reference values and the exploration of how HSEBT reach develops the across the life span. The development of such reference values can be important. Specifically, in an older population they can be useful in fall risk management, since the HSEBT is situation specific to risky movements such as reaching, leaning (Nachreiner et al., 2007) and bending (Duckham et al., 2013).

The HSEBT can be used to measure sports and activity dependent adaptations and characteristics and their influence on performance. In the current study, due to small sport specific sample sizes, we could only explore the influence of activity level and not sport specific adaptations and characteristics. Even if between sport comparisons were not done, we have presented reference data for different winter sports for future comparisons. The authors expect that athletes participating in different sports will have different HSEBT reach capacities. Specifically, sports where the use of the upper extremities is fundamental to the activity (golf, tennis, volleyball, overhead throwing sports etc.) are expected to show greater reach measures as compared to sports where the upper extremities are less important (i.e. soccer). In addition, specific cut-off values for athletic performances can be determined. For instance, it might be that extension movement pattern measurements up to a certain value increase tennis serve speed, while a further increase does not. Such reference and performance specific cut-off values can be useful in the development and rehabilitation of athletes.

5 Conclusion

Flexion movement patterns (L45 and R45 reaches) should be normalized to wingspan, since a significant variation of these measurements is explained by this measure. In fact, only when normalized L45 and R45 reach measurements were compared, group differences for age, sex and activity level became significant. On the contrary, extension movement patterns do not need to be normalized to anthropometric measures since only leg length had a small influence on the L135 reach measurement. Neither anthropometric measures nor age, sex and activity level influence the rotational reaches. Thus, reference and predictive values for research and clinical purposes should be based on flexion movement patterns normalized to wingspan. In a young and adult population it appears that age, sex and activity level influence HSEBT reach measurements.

6 Conflict of Interest

The first author (OE) is a co-founder of Athletic Knowledge AB (Stockholm, Sweden) which commercially distributes a testing mat for HSEBT and SEBT.

7 Author Contributions

The first author (OE) contributed to conception of the idea and design of the study. All authors (OE, PF and JC) contributed to data analysis and writing of the manuscript.

8 Funding

No funding was obtained for the current study

9 Acknowledgments

Ali Ghelem and Jessica Parnevik-Muth for assisting in the development of the HSEBT. Fredrik Sæland, Stavros Litsos, Stian Rekdal Nielsen, Morten Bråten, Claude Lebraux, Jane Paris, Lene Puntervold, Malin Ekeberg, Vedbjørn Vingsand, Magnus Midtun and Lars Arne Andersen for their assistance in the data acquisition.

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11 Data Availability Statement

The datasets for this study can be found in the Harvard Dataverse (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/NONG4X&version=DRAFT)

12 Figure legends

Figure 1. Maximum reach position of HSEBT reaches standing on the right foot

13 Tables

Table 1. Age, anthropometry and HSEBT results (absolute and normalized values) of the athletic and recreational populations

	Athletes													Recreational
Measure	Alpine skiing	Bobsleigh	CC and Biathlon	Curling	Figure skating	Freestyle skiing	Icehockey	Luge	Skeleton	Snowboarding	Ski jumping	Ice skating	Throwing	
Participants	28	9	4	6	14	13	36	17	8	16	1	2	12	57
Age (yrs)	17.5±.5	17.3±.5	17±0	17±0	16.6±.5	17.3±.6	16.6±.5	17.0±.5	17.1±.4	17.3±.6	17.0±0	18.0±0	21.7±1.7	24.6±4.9
Height (cm)	170.9±4.8	170.1±8.7	177.5±5.4	169.8±12.8	164.3±7.6	170.6±8.8	170.9±7.9	174.6±7.7	168.8±5.5	167.9±8.1	162.0	180.5±10.6	174.8±6.5	180.3±7.8
Leg length (cm)	87.7±3.3	87.8±2.9	90.0±2.7	88.3±6.0	83.4±5.5	88.8±5.5	88.7±5.8	89.5±4.4	87.4±3.4	85.1±3.2	85.0	89.0±4.2	89.7±5.4	91.3±5.0
Wingspan (cm)	174.8±5.7	174.6±12.1	178.8±5.6	170.8±16.2	166.6±10.8	172.7±9.4	172.1±10.6	176.8±7.7	170.5±7.0	171.7±9.6	167.0	186.5±13.4	173.9±8.6	180.2±8.1
Arm length (cm)	73.5±3.2	72.9±5.0	73.8±2.2	71.0±6.8	68.9±4.2	71.8±3.8	72.4±4.8	75.1±4.7	71.3±3.2	71.7±40	71.0	77.5±6.4	72.4±4.3	75.0±3.4
L SLS R45 (cm)	80.3±5.6	78.0±6.0	87.0±2.4	76.0±9.2	79.6±6.2	77.4±5.3	77.9±6.4	80.1±7.8	75.9±5.3	78.8±6.2	81.0	90.0±2.8	79.3±5.3	79.1±6.8
L SLS R45 (%)	45.9±2.9	44.7±2.4	48.7±2.6	44.4±2.7	47.8±2.3	44.8±2.5	45.3±3.0	45.3±3.6	44.5±3.1	45.9±3.8	48.5	48.3±2.0	45.7±2.9	43.9±3.1
L SLS L45 (cm)	71.0±6.0	65.7±6.5	75.0±1.6	65.5±9.3	67.1±5.3	64.1±6.2	69.1±6.7	69.2±7.6	68.5±7.2	67.4±8.5	78.0	77.0±4.2	68.0±5.7	67.0±9.6
L SLS L45 (%)	40.6±3.2	37.7±3.4	42.0±1.5	38.4±5.4	40.4±3.6	37.2±3.6	40.2±3.1	39.2±3.9	40.1±3.0	39.4±5.4	46.7	41.5±5.3	39.2±3.6	37.1±4.7
L SLS L135 (cm)	87.4±9.7	87.4±7.0	91.3±9.4	75.2±12.1	92.2±6.5	79.5±13.5	88.1±8.9	91.1±10.0	90.1±4.4	86.2±7.0	90.0	102±2.8	87.8±5.7	83.5±11.3
L SLS R135 (cm)	65.9±13.2	61.8±13.9	63.3±10.9	51.0±12.2	68.8±8.2	59.2±12.0	65.5±11.9	67.7±9.8	63.3±10.1	60.8±12.7	66.0	72.0±14.1	63.3±11.0	55.0±15.0
L SLS LROT (°)	133.3±14.9	126.2±16.2	135.0±12.3	107.8±25.7	127.6±10.7	127.3±16.5	131.9±18.9	138.4±12.6	131.4±13.3	132.8±17.6	150.0	122.0±18.4	118.3±11.6	128.2±17.3
L SLS RROT (°)	136.5±10.4	138.9±13.4	138.8±13.4	123.3±11.0	131.0±11.7	131.1±12.9	135.2±13.9	135.2±14.7	131.8±15.7	139.8±10.1	128.0	143.0±18.4	123.9±9.1	132.1±14.6
R SLS L45 (cm)	81.8±4.9	79.8±4.9	85.8±1.5	77.5±6.8	78.5±6.0	78.6±5.9	78.6±6.3	81.3±6.8	75.5±5.7	79.1±6.1	83.0	87.0±4.2	81.3±4.8	79.6±7.4
R SLS L45 (%)	46.8±2.6	45.8±2.5	48.0±2.1	45.5±4.2	47.1±2.6	45.5±2.4	45.7±2.8	46.0±2.8	44.3±2.4	46.2±3.5	49.7	46.7±1.1	46.8±3.2	44.2±3.3
R SLS R45 (cm)	71.1±6.1	66.2±5.9	72.5±1.3	63.510.0	67.5±5.9	63.4±7.0	68.2±6.6	70.3±7.1	67.0±5.8	67.0±8.4	73.0	79.5±2.1	68.6±6.4	65.6±9.3
R SLS R45 (%)	40.7±3.4	38.0±2.7	40.6±.72	37.2±5.4	38.0±11.3	36.8±4.4	39.6±3.2	39.8±3.7	39.3±2.3	39.1±5.1	43.7	42.8±4.2	39.5±4.3	36.4±4.7
R SLS R135 (cm)	86.5±9.4	85.2±12.9	91.0±8.5	75.3±9.2	92.8±6.5	81.2±12.4	84.7±8.4	90.2±8.3	89.1±6.0	83.5±7.1	83.0	104.0±0.0	87.3±5.9	80.8±12.5
R SLS L135 (cm)	69.3±12.8	66.2±17.1	65.3±10.4	49.7±11.2	68.9±8.8	60.9±12.0	66.8±10.3	68.6±10.3	69.6±10.3	60.4±12.9	59.0	67.5±17.7	62.5±11.7	65.6±9.3
R SLS RROT (°)	132.5±17.8	127.4±16.0	129.0±22.8	107.0±20.1	126.1±10.1	123.9±16.3	132.6±15.3	136.8±13.7	126.4±18.9	130.4±11.4	135.0	125.0±14.1	115.92±11.5	126.5±17.4
R SLS LROT (°)	136.6±12.2	135.9±20.4	146.8±18.1	124.0±14.3	131.7±8.5	132.0±15.1	134.9±14.4	136.5±9.8	137.6±14.6	138.1±16.7	130.0	128.5±5.0	124.2±7.8	132.1±14.6

Notes. Values are means±standard deviations; CC=Cross country skiing; R=Right, L=Left; 45=45 degree relative to anterior surface of body; 135=135 degrees relative to anterior surface of body: ROT=Rotation; %=normalized HSEBT values (reach measurement/wingspan·100)

Table 2. Age, anthropometry and HSEBT results (absolute and normalized values) grouped by gender, age and activity level with group comparisons

	Male	**Female**	***d***	**p**	**Young**	**Adult**	***d***	**p**	**Athletes**	**Recreational**	***d***	**p**	**MDC**
n	133	90			159	64			166	57			
Age (yrs)	20.2±4.3	17.6±1.8	.83	<.001	17.1±.6	24.3±3.4	12.5	<.001	17.4±1.4	24.1±3.9	2.00	<.001	
Height (cm)	177.5±7.1	167.1±6.7	1.51	<.001	170.6±8.0	179.6±7.0	1.17	<.001	170.7±7.9	180.4±6.8	1.26	<.001	
Leg length (cm)	90.3±4.6	86.1±4.5	.94	<.001	87.5±4.6	91.2±5.0	.78	<.001	87.7±4.7	91.3±4.4	.79	<.001	
Wingspan (cm)	179.4±8.2	168.5±7.9	1.35	<.001	173.0±9.6	179.4±8.5	.68	<.001	173.0±9.6	180.2±8.1	.77	<.001	
Arm length (cm)	75.0±3.3	70.3±3.6	1.38	<.001	72.4±4.3	74.7±3.7	.56	<.001	72.4±4.3	75.0±3.4	.64	<.001	
R45 (cm)	80.1±6.4	78.4±5.8	.28	.043	79.3±6.0	79.4±6.3	.01	.942	79.4±5.9	79.4±6.9	.01	.928	1.5-2.1
R45 NORM (%)	44.7±2.9	46.5±2.8	.64	<.001	45.9±2.8	44.4±3.2	.50	.001	45.9±2.8	44.0±3.1	.66	<.001	NE
L45 (cm)	68.1±7.6	68.4±6.0	.04	.760	68.3±6.8	67.7±7.8	.08	.583	68.4±6.7	67.5±7.8	.13	.396	2.4-2.8
L45 NORM (%)	38.0±3.9	40.6±3.1	.72	<.001	39.6±3.5	37.7±4.0	.50	.001	39.7±3.5	37.2±3.9	.67	<.001	NE
L135 (cm)	85.6±9.6	87.3±7.8	.19	.181	87.0±8.7	84.9±8.7	.24	.110	87.5±8.2	83.4±9.6	.48	.003	3.9-4.2
R135 (cm)	60.7±13.3	65.3±9.7	.41	.004	64.5±11.6	56.9±14.6	.55	<.001	65.0±11.1	54.5±14.9	.75	<.001	7.2-7.9
LROT (°)	128.3±16.1	129.8±13.1	.10	.462	130.0±13.7	125.5±16.5	.31	.038	129.2±14.0	127.3±16.6	.12	.426	6.3-7.2
RROT (°)	134.4±13.1	133.1±10.5	.11	.431	134.8±11.1	132.6±14.0	.17	.211	134.9±11.3	134.7±14.1	.06	.679	4.7-5.2

Abbreviations: Values are means±standard deviations; R=Right, L=Left; 45=45 degree relative to anterior surface of body; 135=135 degrees relative to anterior surface of body: ROT=Rotation; ; %=normalized HSEBT values (reach measurement/wingspan·100); MDC=Minimal detectable change; NE=Not established

Table 3. Stepwise multiple linear regression of HSEBT tests

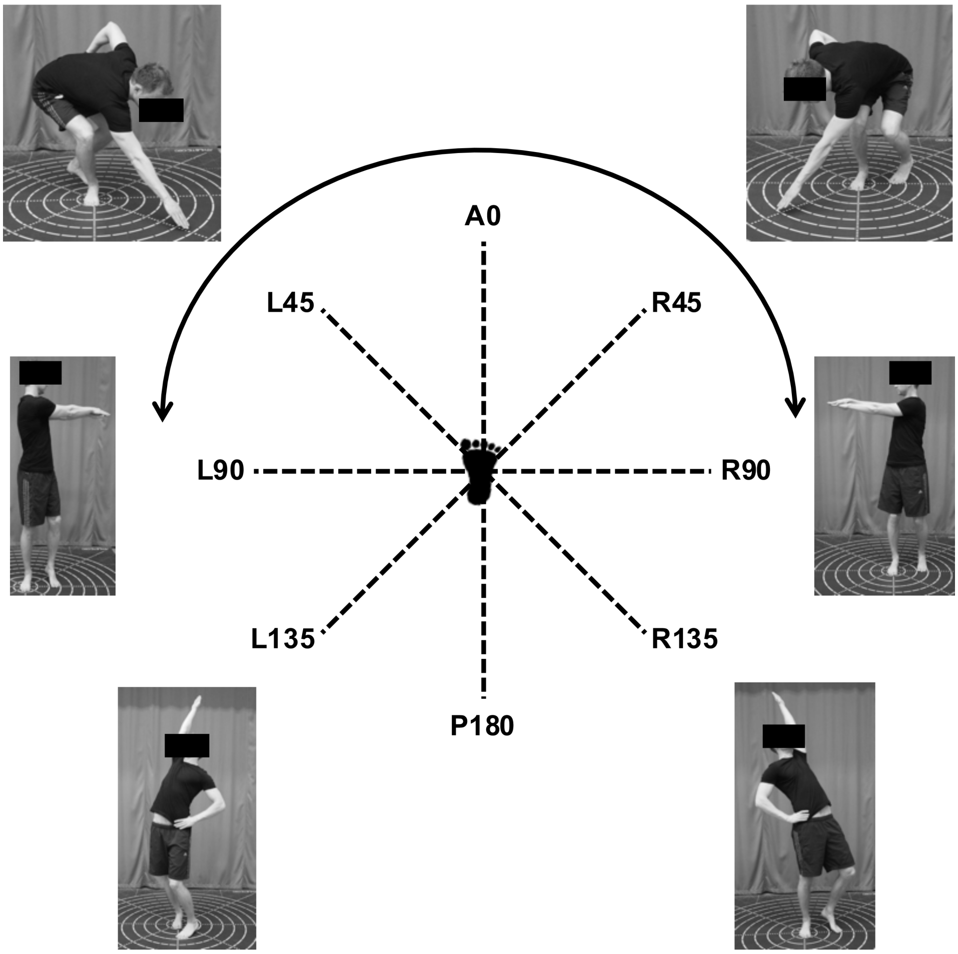
Test	***B***	**SE *B***	**B**	**R^2**
R45 Step 1				
Constant	11.96	7.22		
Wingspan	.39	.041	.59**	.346
R45 Step 2				
Constant	-3.93	8.45		
Wingspan	.47	.047	.62**	
Sex	3.07	.92	.24**	.388 (ΔR^2= .042)
R45 Step 3				
Constant	.62	8.58		
Wingspan	.58	.069	.89**	
Sex	3.1	.90	.24**	
Leg length	-.279	.12	-.22*	.407 (ΔR^2= .019)
L45 Step 1				
Constant	22.71	9.69		
Wingspan	.26	.055	.34**	.117
L45 Step 2				
Constant	-3.86	11.13		
Wingspan	.40	.062	.53**	
Sex	5.15	1.21	.35**	.206 (ΔR^2= .089)
L135 Step 1				
Constant	87,38	.83		
Activity	-3.86	1.67	-.18*	.033
L135 Step 2				
Constant	59.67	12.86		
Activity	-4.64	1.69	-22**	
Leg length	.32	.15	.17*	.060 (ΔR^2=.027)
R135				
Constant	64.68	1.08		
Activity	-7.21	2.17	-	.065
RROT				
NE				
LROT				
NE				

*p<.05
**p<.01
***p<.001
Abbreviations: B=Unstandardized coefficient; β=Standardized beta coefficient; SE=Standard error; R^2: Coefficient of determination; NE=No variables entered into the equation; R=Right, L=Left; 45=45 degree relative to anterior surface of body; 135=135 degrees relative to anterior surface of body: ROT=Rotation.

Appendix 1. Validation of the multiple linear regression of HSEBT tests

	Initial model (75%)				Validation model (25%)			
Test	***B***	**SE *B***	**B**	**R^2**	***B***	**SE *B***	**B**	**R^2**
R45 Step 1								
Constant	11.96	7.22						
Wingspan	.39	.041	.59**	.346				
R45 Step 2								
Constant	-3.93	8.45						
Wingspan	.47	.047	.62**					
Sex	3.07	.92	.24**	.388 (ΔR^2= .042)				
R45 Step 3					Forced entry			
Constant	.62	8.58			13.85	14.944		
Wingspan	.58	.069	.89**		.30	.14	.52*	
Sex	3.1	.90	.24**		2.27	1.73	.22	
Leg length	-.279	.12	-.22*	.407 (ΔR^2= .019)	.135	.242	.12	.288
L45 Step 1								
Constant	22.71	9.69						
Wingspan	.26	.055	.34**	.117				
L45 Step 2					Forced entry			
Constant	-3.86	11.13			13.00	17.11		
Wingspan	.40	.062	.53**		.32	.095	.50**	
Sex	5.15	1.21	.35**	.206 (ΔR^2= .089)	.93	2.02	.068	.215
L135 Step 1								
Constant	87,38	.83						
Activity	-3.86	1.67	-.18*	.033				
L135 Step 2					Forced entry			
Constant	59.67	12.86			44.16	19.64		
Activity	-4.64	1.69	-22**		-7.35	2.71	-.42**	
Leg length	.32	.15	.17*	.060 (ΔR^2=.027)	.49	.22	.34*	.134
R135					Forced entry			
Constant	64.68	1.08			66.07	1.69		
Activity	-7.21	2.17	-	.065	-14.20	3.17	-.53***	.28
RROT					Forced entry			
NE					NE			
LROT					Forced entry			
NE					NE			

*p<.05
**p<.01
***p<.001
Abbreviations: B=Unstandardized coefficient; β=Standardized beta coefficient; SE=Standard error; R^2: Coefficient of determination; NE=No variables entered into the equation; R=Right, L=Left; 45=45 degree relative to anterior surface of body; 135=135 degrees relative to anterior surface of body: ROT=Rotation.


A0
L45
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Appendices

Appendix I:

Reliability reaching tests

Appendix II:

Reliability hopping tests

Appendix III:

Reliability landing tests

Appendix IV:

Reliability functional mobility tests

Appendix V:

HSEBT test description

Appendix VI:

Approval letters from the Norwegian Centre for Research Data

Appendix VII:

Study IV: Warm-up procedures

Appendix VIII:

Marker set study I

Appendix IX:

Validation of multiple linear regression of HSEBT outcome measurements

Appendix I. Reliability reaching tests

Test	Populations	Measurement(s)	Reliability
Star excursion balance test (SEBT)	**Recreational/healthy** (Glave et al., 2016; P. A. Gribble, Brigle, Pietrosimone, Pfile, & Webster, 2013; Hertel et al., 2000; Hyong & Kim, 2014; Kinzey & Armstrong, 1998; Lopez-Plaza et al., 2018; Munro & Herrington, 2010) **Patients** (Bastien et al., 2014a) **Male** (Bastien et al., 2014a; Glave et al., 2016; P. A. Gribble, Brigle, et al., 2013; Hertel et al., 2000; Hyong & Kim, 2014; Kinzey & Armstrong, 1998; Lopez-Plaza et al., 2018; Munro & Herrington, 2010) **Female** (Glave et al., 2016; P. A. Gribble, Brigle, et al., 2013; Hertel et al., 2000; Hyong & Kim, 2014; Kinzey & Armstrong, 1998; Munro & Herrington, 2010)	**Quantitative** Maximum reach (cm) commonly normalized to leg length (%) or composite score (sum of reaches) (P. A. Gribble et al., 2012).	**Inter-rater** ICC: 0.81 to 0.94 (P. A. Gribble, Kelly, et al., 2013; Hertel et al., 2000; Hyong & Kim, 2014) SEM: 3.2 to 4.3% (Hyong & Kim, 2014) SEM: 2.3 to 3.9 cm (Hertel et al., 2000) MDC: 8.9 to 11.8% (Hyong & Kim, 2014) **Intra-rater** ICC: 0.82 to 0.96 (Hertel et al., 2000; Hyong & Kim, 2014) SEM: 2.4 to 3.3% (Hyong & Kim, 2014) MDC: 6.7 to 9.2% (Hyong & Kim, 2014) **Test-retest** ICC: 0.62 to 0.92 (Kinzey & Armstrong, 1998; Lopez-Plaza et al., 2018; Munro & Herrington, 2010) SEM: 2.12 to 5.94% (Lopez-Plaza et al., 2018; Munro & Herrington, 2010) SEM: 3.4 to 4.0 cm (Kinzey & Armstrong, 1998) MDC: 4.11 to 8.91% (Lopez-Plaza et al., 2018; Munro & Herrington, 2010) MDC: 5.4 to 7.0 cm (Munro & Herrington, 2010)
		Qualitative Criterion based rating of movement and position of arms, trunk, pelvis and knee relative to 2nd toe and loss of balance (Ness et al., 2015; Piva et al., 2006).	**Inter-rater** Trunk and pelvis: Kappa = 0.18 to 0.60 (Ness et al., 2015) Knee: Kappa = 0.5 to 0.6 (Ness et al., 2015) Total movement score: Kappa = 0.64 to 0.73 (Ness et al., 2015)
Y-balance reach test (YBT)	**Athletes** (Kenny et al., 2018; Linek, Sikora, Wolny, & Saulicz, 2017; Plisky et al., 2006) **Recreational/healthy** (Almeida et al., 2017; Calatayud et al., 2014; Clark et al., 2010; Freund et al., 2018; Fusco et al., 2018; Ness et al., 2015) **Patients** (Almeida et al., 2017; Shaffer et al., 2013) **Male** (Almeida et al., 2017; Clark et al., 2010; Faigenbaum et al., 2014; Fusco et al., 2018; Linek et al., 2017; Ness et al., 2015 ; Plisky et al., 2006; Shaffer et al., 2013) **Female** (Almeida et al., 2017; Clark et al., 2010; Faigenbaum et al., 2014; Freund et al., 2018; Fusco et al., 2018; Ness et al., 2015; Plisky et al., 2006; Shaffer et al., 2013) **Children** (Calatayud et al., 2014; Faigenbaum et al., 2014)	**Quantitative** Same as SEBT.	**Intra-rater** ICC: 0.57 to 0.93 (Linek et al., 2017; Plisky et al., 2009; Plisky et al., 2006; van Lieshout et al., 2016) SEM: 0.7 to 5.9% (Linek et al., 2017; van Lieshout et al., 2016) SEM: 2.0 to 5.8 cm (Plisky et al., 2009) CV: 2.0 to 2.9% (Plisky et al., 2006) MDC: 1.8 to 13.7% (Linek et al., 2017; van Lieshout et al., 2016) **Inter-rater** ICC: 0.80 to 1.00 (Almeida et al., 2017; Clark et al., 2010; Faigenbaum et al., 2014; Freund et al., 2018; Plisky et al., 2009; van Lieshout et al., 2016) SEM: 0 to 4.4% (Freund et al., 2018; van Lieshout et al., 2016) SEM: 0 to 3.3 cm (Freund et al., 2018; Plisky et al., 2009) MDC: 0 to 12.3% (Freund et al., 2018; van Lieshout et al., 2016) MDC: 0 to 2.6 cm (Freund et al., 2018) **Test-retest** ICC: 0.51 to 0.98 (Calatayud et al., 2014; Clark et al., 2010; Faigenbaum et al., 2014; Freund et al., 2018; Kenny et al., 2018; Plisky et al., 2006; Shaffer et al., 2013) SEM: 1.9 to 12.32% (Calatayud et al., 2014; Freund et al., 2018) SEM: 1.7 to 5.4 cm (Freund et al., 2018; Kenny et al., 2018; Shaffer et al., 2013) MDC: 5.36 to 34.15% (Calatayud et al., 2014; Freund et al., 2018)

			MDC: 4.7 to 15.0 cm (Freund et al., 2018; Kenny et al., 2018; Shaffer et al., 2013) CV: 3.6 to 4.4% (Plisky et al., 2006)
		Qualitative Same as SEBT	**Inter-rater** Trunk and pelvis: Kappa = 0.18 to 0.43 (Ness et al., 2015) Knee: Kappa = 0.5 to 0.6 (Ness et al., 2015)
Seated reach test (SRT)	**Recreational/healthy** (Field-Fote & Ray, 2010; Katz-Leurer et al., 2009; Radtka et al., 2017) **Patients** (Field-Fote & Ray, 2010; Katz-Leurer et al., 2009; Lynch et al., 1998) **Male** (Field-Fote & Ray, 2010; Radtka et al., 2017; Thompson & Medley, 2007) **Female** {Field-Fote, 2010 #2005;Radtka, 2017 #2006; Lynch, 1998 #2008; Thompson, 2007 #2009} **Children** (Radtka et al., 2017) {Abellaneda, 2009 #719}	**Quantitative** Maximum reach (cm) (Field-Fote & Ray, 2010; Radtka et al., 2017; Thompson & Medley, 2007).	**Test-retest** ICC: 0.78 to 0.99 (Field-Fote & Ray, 2010; Katz-Leurer et al., 2009; Radtka et al., 2017) SEM: 2.0 to 4.0 cm (Radtka et al., 2017) **Test-retest without foot support** ICC: 0.80 to 0.96 (Radtka et al., 2017) SEM: 3.4 to 8.9 cm (Radtka et al., 2017) **Intra-rater** ICC: 0.85 to 0.98 (Lynch et al., 1998; Thompson & Medley, 2007)
Functional reach test (FR)	**Recreational/healthy** (Brauer et al., 1999; Duncan et al., 1990; Giorgetti, Harris, & Jette, 1998; Lin et al., 2012; Newton, 2001) **Disabled** (Giorgetti et al., 1998) **Male** (Duncan et al., 1990; Giorgetti et al., 1998; Lin et al., 2012; Newton, 2001) **Female** (Brauer et al., 1999; Duncan et al., 1990; Giorgetti et al., 1998; Lin et al., 2012; Newton, 2001) Elderly (Giorgetti et al., 1998)	**Quantitative** Reach distance (cm) (Newton, 2001) and COP excursion (Brauer et al., 1999; Duncan et al., 1990)	**Functional reach test-retest** ICC: 0.91 to 0.92 (Duncan et al., 1990 Lin, 2012 #1707) SEM: 2.1 to 2.4 cm (Lin et al., 2012) **Functional reach inter-rater (within session)** ICC: 0.99 (Lin et al., 2012) SEM: 0 to 0.8 cm (Lin et al., 2012) **Functional reach inter-rater (between session)** ICC: 0.73 to 0.92 (Giorgetti et al., 1998; Lin et al., 2012) SEM: 2.1 to 2.3 cm (Lin et al., 2012) **Lateral reach test-retest** ICC: 0.99 (Brauer et al., 1999) **Multidirectional reach test-retest** ICC: forward: 0.94; lateral: 0.93 and 0.94; backward: 0.93 (Newton, 2001) **Inter-rater (within session)** ICC: 0.99 (Lin et al., 2012) **Inter-rater (between session)** ICC: 0.73 to 0.92 (Giorgetti et al., 1998; Lin et al., 2012)
Closed kinetic chain upper extremity stability test (CKCUEST)	**Recreational/healthy** (Goldbeck & Davies, 2000; Tucci et al., 2014) **Male** (Goldbeck & Davies, 2000; Tucci et al., 2014) **Female** (Tucci et al., 2014)	**Quantitative** Number of touches in 15 seconds (Goldbeck & Davies, 2000; Tarara et al., 2016)	**Test-retest intrasession** ICC: 0.90 to 0.96 (Goldbeck & Davies, 2000; Tucci et al., 2014) SEM: 1.45 to 2.76 (Tucci et al., 2014) MDC: 2.05 to 3.91 (Tucci et al., 2014) **Test-retest intersession** ICC: 0.85 to 0.96 (Tucci et al., 2014)

Upper quarter Y-balance reach test (UQYBT)	**Recreational/healthy** (Borms et al., 2016; Gorman, Butler, Plisky, et al., 2012; Westrick et al., 2012) **Male** (Borms et al., 2016; Gorman, Butler, Plisky, et al., 2012; Westrick et al., 2012) **Female** (Gorman, Butler, Plisky, et al., 2012);Westrick, 2012 #1926;Borms, 2016 #2069}	**Quantitative** Maximum reaches (cm) normalized to arm length or composite score (sum of reaches) (Gorman, Butler, Plisky, et al., 2012).	**Test-retest composite score** ICC: 0.80 to 0.99 (Gorman, Butler, Plisky, et al., 2012; Westrick et al., 2012) SEM: 2.2 to 2.9 cm (Gorman, Butler, Rauh, et al., 2012) MDC: 6.1 to 8.1 cm (Gorman, Butler, Rauh, et al., 2012) **Inter-rater composite score** ICC: 1.00 (Gorman, Butler, Plisky, et al., 2012)

Note: ICC = Intraclass correlation coefficient; SEM = Standard error of measurement; CV = Coefficient of variation; MDC = Minimal detectable change.

Appendix II. Reliability hopping tests

Test	Populations	Measurement(s)	Reliability
Multiple hop	**Patients** (Eechaute et al., 2008, 2009) **Male** (Eechaute et al., 2008, 2009; Riemann & Caggiano, 1999) **Female** (Eechaute et al., 2008, 2009; Riemann & Caggiano, 1999)	**Quantitative** Time (s) (Eechaute et al., 2008).	**Test-retest** ICC: 0.87 to 0.97 (Eechaute et al., 2008) SEM: 1.9 to 2.3 seconds (Eechaute et al., 2008)
		Qualitative Balance errors counted for 30 hops on each foot (Eechaute et al., 2009) or count of balance and landing errors (Riemann & Caggiano, 1999).	**Test-retest balance score** ICC: 0.64 to 0.83 (Eechaute et al., 2009) SEM: 2.6 to 2.8 errors (Eechaute et al., 2009) **Intra-rater balance score** ICC: 0.83 to 0.94 (Eechaute et al., 2009) **Inter-rater balance score** ICC: 0.91 to 0.94 (Eechaute et al., 2009) **Inter-tester balance score** ICC: 0.70 to 0.74 (Riemann & Caggiano, 1999) SEM: 0.54 to 0.55 (Riemann & Caggiano, 1999) **Inter-tester landing score** ICC: 0.92 (Riemann & Caggiano, 1999) SEM: 0.56 to 0.57 (Riemann & Caggiano, 1999)
Single leg hop	**Athletes** (Barber et al., 1990; Haitz et al., 2014) **Recreational/healthy** (Augustsson et al., 2006; Barber et al., 1990; Bolgla & Keskula, 1997; Munro & Herrington, 2011; Ramirez et al., 2018) **Patients** (Ageberg, Zatterstrom, & Moritz, 1998; Barber et al., 1990; Reid et al., 2007) **Male** (Ageberg et al., 1998; Augustsson et al., 2006; Barber et al., 1990; Bolgla & Keskula, 1997; Haitz et al., 2014; Munro & Herrington, 2011; Ramirez et al., 2018; Reid et al., 2007) **Female** (Ageberg et al., 1998; Barber et al., 1990; Bolgla & Keskula, 1997; Haitz et al., 2014; Munro & Herrington, 2011; Ramirez et al., 2018; Reid et al., 2007)	**Quantitative** Distance (m), percentage of leg length (LL%) (Barber et al., 1990) or limb symmetry index (LSI) > 85% is normal (Barber et al., 1990; Reid et al., 2007).	**Test-retest distance** ICC: 0.75 to 0.96 (Ageberg et al., 1998; Augustsson et al., 2006; Bolgla & Keskula, 1997; Brosky, Nitz, Malone, Caborn, & Rayens, 1999; Haitz et al., 2014; Munro & Herrington, 2011; Reid et al., 2007) SEM: 4.56 to 7.7 cm (Bolgla & Keskula, 1997; Haitz et al., 2014) SEM: 7.87 to 7.93 %LL (Munro & Herrington, 2011) CV: 5.1 to 7.8% (Augustsson et al., 2006). MDC: 21.3 cm (Haitz et al., 2014) MDC: 21.81 to 21.98 %LL (Munro & Herrington, 2011) **Inter-rater distance** ICC: 1.00 (Haitz et al., 2014) SEM: 7,7 cm (Haitz et al., 2014) MDC: 4.8 cm (Haitz et al., 2014) **Test-retest LSI** ICC: 0.92 (Reid et al., 2007) SEM: 3.49% (Reid et al., 2007) MDC: 8.09% (Reid et al., 2007)
		Qualitative Postural Orientation Error (POE) is a seven segment specific rating on a four point ordinal scale (0-3) with 0 as good and 3 as very poor of 1) arm, 2) trunk, 3) hip joint, 4) medial knee-to-foot position (MKFP), 5) foot pronation, 6) kinematic asymmetry and 7) joint flexion on landing (Nae et al., 2017).	**Inter-rater** Overall test battery ICC: 0.84 (Nae et al., 2017) Weighted kappa: 0.686 to 0.875 (Nae et al., 2017)

		Qualitative Knee flexion in landing (11-point scale) (von Porat et al., 2008)	**Inter-rater** ICC: 0.57 to 0.76 (von Porat et al., 2008)
		Qualitative Peak knee valgus angle (°) during landing (Ramirez et al., 2018)	**Inter-rater visual estimation** ICC: 0.68 to 0.69 (Ramirez et al., 2018) SEM: 3.25 to 3.89° (Ramirez et al., 2018) MDC: 4.6 to 5.5° (Ramirez et al., 2018) **Inter-rater video analysis** ICC: 0.79 to 0.93 (Ramirez et al., 2018) SEM: 1.64 to 2.71° (Ramirez et al., 2018) MDC: 2.32 to 3.83° (Ramirez et al., 2018)
Triple hop	**Athletes** (Haitz et al., 2014) **Patients** (Reid et al., 2007) **Male** (Bolgla & Keskula, 1997; Haitz et al., 2014; Munro & Herrington, 2011; Reid et al., 2007) **Female** (Bolgla & Keskula, 1997; Haitz et al., 2014; Munro & Herrington, 2011; Reid et al., 2007)	**Quantitative** Distance (m), percentage of leg length (LL%) and LSI (Reid et al., 2007).	**Test-retest distance** ICC: 0.80 to 0.95 (Bolgla & Keskula, 1997; Haitz et al., 2014; Munro & Herrington, 2011) SEM: 15.44 to 25.1 cm (Bolgla & Keskula, 1997; Haitz et al., 2014) SEM: 17.17 to 23.18 %LL (Munro & Herrington, 2011) MDC: 69.7 cm (Haitz et al., 2014) MDC: 47.59 to 64.25 %LL (Munro & Herrington, 2011) **Inter-rater distance** ICC: 1.00 (Haitz et al., 2014) SEM: 5.6 cm (Haitz et al., 2014) MDC: 15.5 cm (Haitz et al., 2014) **Test-retest LSI** ICC: 0.88 (Reid et al., 2007) SEM: 4.32% (Reid et al., 2007) MDC: 10.02% (Reid et al., 2007)
6-m timed hop	**Athletes** (Haitz et al., 2014) **Patients** (Brosky et al., 1999; Reid et al., 2007) **Male** (Bolgla & Keskula, 1997; Brosky et al., 1999; Haitz et al., 2014; Reid et al., 2007) **Female** (Bolgla & Keskula, 1997; Haitz et al., 2014; Reid et al., 2007)	**Quantitative** Time (s) and LSI (Reid et al., 2007).	**Test-retest time** ICC: 0.60 to 0.92 (Bolgla & Keskula, 1997; Brosky et al., 1999; Haitz et al., 2014; Munro & Herrington, 2011) SEM: 0.1 to 0.13 s (Bolgla & Keskula, 1997; Haitz et al., 2014) MDC: 0.076 to 0.3 s (Haitz et al., 2014; Munro & Herrington, 2011) **Inter-rater time** ICC: 0.93 (Haitz et al., 2014) SEM: 0.1 s (Haitz et al., 2014) MDC: 0.3 s (Haitz et al., 2014) **Test-retest LSI** ICC: 0.82 (Reid et al., 2007) SEM: 5.59% (Reid et al., 2007) MDC: 12.96% (Reid et al., 2007)

Cross over hop	**Athletes** (Haitz et al., 2014; Kivlan et al., 2013) **Patients** (Reid et al., 2007) **Male** (Bolgla & Keskula, 1997; Haitz et al., 2014; Munro & Herrington, 2011; Reid et al., 2007) **Female** (Bolgla & Keskula, 1997; Haitz et al., 2014; Kivlan et al., 2013; Munro & Herrington, 2011; Reid et al., 2007)	**Quantitative** Distance (m) and LSI (Reid et al., 2007).	**Test-retest distance** ICC: 0.86 to 0.96 (Bolgla & Keskula, 1997; Haitz et al., 2014; Munro & Herrington, 2011) SEM: 15.95 to 26.1cm (Bolgla & Keskula, 1997; Haitz et al., 2014) SEM: 19.73 to 21.16 %LL (Munro & Herrington, 2011) MDC: 72.5 cm (Haitz et al., 2014) MDC: 54.69 to 58.65 %LL (Munro & Herrington, 2011) **Inter-rater distance** ICC: 1.00 (Haitz et al., 2014) SEM: 4.7 cm (Haitz et al., 2014) MDC: 13.0 cm (Haitz et al., 2014) **Test-retest LSI** ICC: 0.84 (Reid et al., 2007) SEM: 5.28% (Reid et al., 2007) MDC: 8.66% (Reid et al., 2007)
		Quantitative Time (s)	**Test-retest time** ICC: 0.89 (Kivlan et al., 2013) SEM: 0.15 s (Kivlan et al., 2013) MDC: 0.42 s (Kivlan et al., 2013)
		Qualitative Knee flexion in landing (11-point scale) (von Porat et al., 2008)	**Inter-rater** ICC: 0.57 to 0.76 (von Porat et al., 2008)
Four hops, three contacts (4H3C)	**Patients** (Mani et al., 2017) **Male** (Mani et al., 2017) **Female** (Mani et al., 2017)	**Quantitative** Hop distances (m) and contact time (s) (Mani et al., 2017).	**Test-retest distance** ICC: 0.91 to 0.96 (Mani et al., 2017) TE: 3.6 to 5.2% (Mani et al., 2017) **Test-retest contact time** ICC: 0.75 to 0.88 (Mani et al., 2017) TE: 7.3 to 10.9% (Mani et al., 2017)
One-arm hop test	**Athletes** (Falsone et al., 2002) **Male** (Falsone et al., 2002)	**Quantitative** Time (s) (Falsone et al., 2002)	**Test-retest** ICC: 0.78 to 0.81 (Falsone et al., 2002)

Note: ICC = Intraclass correlation coefficient; SEM = Standard error of measurement; CV = Coefficient of variation; MDC = Minimal detectable change; TE = Typical error.

Appendix III. Reliability landing tests

Test	Populations	Measurement(s)	Reliability
Forward jump landing (FJL)	**Athletes** (Troester et al., 2018) **Recreational/healthy** (Krkeljas, 2018; Ross et al., 2005; Sell, 2012; Wikstrom, Tillman, et al., 2006; Wikstrom et al., 2005) **Patients** (Ross et al., 2005) **Male** (Krkeljas, 2018; Ross et al., 2005; Sell, 2012; Troester et al., 2018; Wikstrom, Tillman, et al., 2006; Wikstrom et al., 2005) **Female** (Ross et al., 2005; Sell, 2012; Wikstrom, Tillman, et al., 2006; Wikstrom et al., 2005)	**TTS** **DPSI** **rPVGRF** **rIMP**	**Test-retest TTS AP** ICC: 0.79 to 0.80 (Ross et al., 2005; Wikstrom et al., 2005) SEM: 0.055 to 0.15s (Ross et al., 2005; Wikstrom et al., 2005) **Test-retest TTS ML** ICC: 0.27 to 0.66 (Ross et al., 2005; Wikstrom et al., 2005) SEM: 0.21 to 0.26s (Ross et al., 2005; Wikstrom et al., 2005) **Test-retest TTS V** ICC: 0.28 to 0.97 (Colby et al., 1999; Troester et al., 2018; Wikstrom et al., 2005) SEM: 0.29 s (Wikstrom et al., 2005) CV: 13 to 21% (Troester et al., 2018) TE: 0.08 to 0.13 (Troester et al., 2018) **Test-retest DPSI** ICC: 0.86 to 0.96 (Sell, 2012; Wikstrom et al., 2005) SEM: 0.01 to 0.03 (Sell, 2012; Wikstrom et al., 2005) **Test-retest MLSI** ICC: 0.26 to 0.38 (Wikstrom, Tillman, et al., 2006; Wikstrom et al., 2005) SEM: 0.06 (Wikstrom et al., 2005) **Test-retest APSI** ICC: 0.86 to 0.90 (Wikstrom, Tillman, et al., 2006; Wikstrom et al., 2005) SEM: 0.02 (Wikstrom et al., 2005) **Test-retest VSI** ICC: 0.97 (Wikstrom, Tillman, et al., 2006; Wikstrom et al., 2005) SEM: 0.03 (Wikstrom et al., 2005) **Test-retest rPVGRF** ICC: 0.58 to 0.71 (Troester et al., 2018) TE: 0.57 to 0.67 (Troester et al., 2018) CV: 12 to 14% (Troester et al., 2018) **Test-retest rIMP** ICC: 0.64 to 0.68 (Troester et al., 2018) TE: 0.15 to 0.17 (Troester et al., 2018) CV: 7 to 8% (Troester et al., 2018) **Inter-trial TTS V** ICC: 0.22 to 0.27 (Troester et al., 2018) CV: 25 to 29% (Troester et al., 2018) TE: 0.15 to 0.19 (Troester et al., 2018) **Inter-trial TTS ML** ICC: 0.97 (Meardon et al., 2016) **Inter-trial TTS AP** ICC: 0.99 (Meardon et al., 2016) **Inter-trial MLSI** ICC: 0.68 (Meardon et al., 2016) **Inter-trial APSI**

			ICC: 0.99 (Meardon et al., 2016) **Inter-trial VSI** ICC: 0.99 (Meardon et al., 2016) **Inter-trial DPSI** ICC: 0.99 (Meardon et al., 2016) **Inter-trial rPVGRF** ICC: 0.69 to 0.72 (Troester et al., 2018) CV: 13 to 15% (Troester et al., 2018) TE: 0.62 to 0.71 (Troester et al., 2018) **Inter-trial rIMP** ICC: 0.54 to 0.65 (Troester et al., 2018) CV: 9 to 11% (Troester et al., 2018) TE: 0.15 to 0.18 (Troester et al., 2018)
Forward hop at 75% max distance (75% Hop)	**Athletes** (Read et al., 2016) **Male** (Read et al., 2016)	**TTS** **PVGRF** **Time to PVGRF**	**Test-retest TTS V:** ICC: 0.09 to 0.25 (Read et al., 2016) CV: 35.2 to 43.6% (Read et al., 2016) **Test-retest PVGRF** ICC: 0.62 to 0.91 (Read et al., 2016) CV: 6.1 to 10.2% (Read et al., 2016) **Test-retest time to PVGRF** ICC: 0.57 to 0.62 (Read et al., 2016) CV: 20 to 22.5% (Read et al., 2016)
Lateral jump landing	**Recreational/healthy** (Sell, 2012) **Male** (Sell, 2012) **Female** (Sell, 2012)	**DPSI**	**Test-retest DPSI** ICC: 0.86 (Sell, 2012) SEM: 0.01 (Sell, 2012)
Diagonal forward jump landing	No studies identified	No studies identified	No studies identified
Forward drop landing (LDL)	**Athletes** (Krkeljas, 2018) **Recreational/healthy** (Bolt, Giger, Wirth, & Swanenburg, 2018) **Patients** (Bolt et al., 2018) **Male** (Bolt et al., 2018; Krkeljas, 2018) **Female** (Bolt et al., 2018)	**TTS**	**Test-retest TTS AP** ICC: 0.13 (Bolt et al., 2018) **Test-retest TTS ML** ICC: 0.62 (Bolt et al., 2018)
Lateral drop landing (LDL)	**Athletes** (Krkeljas, 2018) **Recreational/healthy** (Bolt et al., 2018; Sell, 2012) **Patients** (Bolt et al., 2018; Huang et al., 2014) **Male** (Bolt et al., 2018; Huang et al., 2014; Krkeljas, 2018; Sell, 2012) **Female** (Bolt et al., 2018; Huang et al., 2014; Sell, 2012)	**TTS** **DPSI**	**Test-retest TTS AP** ICC: 0.30 (Bolt et al., 2018) **Test-retest TTS ML** ICC: 0.45 (Bolt et al., 2018)
Medial drop landing	No studies identified	No studies identified	No studies identified

Drop and stick	**Athletes** (Tran et al., 2015) **Male** (Tran et al., 2015) **Female** (Tran et al., 2015)	**TTS** **rPVGRF**	**Inter-trial TTS V** ICC: 0.82-0.90 (Tran et al., 2015) CV: 5.3 to 10.0% (Tran et al., 2015) **Inter-trial rPVGRF** ICC: 0.62 to 0.76 (Tran et al., 2015) CV: 7.7 to 16.2% (Tran et al., 2015)
Drop-jump	**Athletes** (Mohammadi et al., 2012; Read et al., 2016) **Patients** (Mohammadi et al., 2012) **Male** (Mohammadi et al., 2012; Padua et al., 2009; Read et al., 2016) **Female** (Mohammadi et al., 2012; Padua et al., 2009)	**PVGRF** **Time to PVGRF** **Landing rPVGRF** **Take-off rPVGRF** **Loading rate** **LESS**	**Test-retest landing rPVGRF** ICC: 0.74 to 0.81 (Mohammadi et al., 2012) SEM: 1.6 to 2.4 (unit not identified) (Mohammadi et al., 2012) **Test-retest take-off rPVGRF** ICC: 0.76 to 0.80 (Mohammadi et al., 2012) SEM: 1.2 to 2.2 (unit not identified) (Mohammadi et al., 2012) **Test-retest loading rate** ICC: 0.74 to 0.82 (Mohammadi et al., 2012) SEM: 1.4 to 2.6 (Mohammadi et al., 2012) **Test-retest PVGRF** ICC: 0.50 to 0.76 (Read et al., 2016) CV: 13.8 to 20.5% (Read et al., 2016) **Test-retest time to PVGRF** ICC: 0.54 to 0.77 (Read et al., 2016) CV: 23 to 49.7% (Read et al., 2016) **Inter-rater LESS** ICC: 0.84 (Padua et al., 2009) SEM: 0.71 (Padua et al., 2009)
Single leg counter movement jump	**Athletes** (Read et al., 2016) **Male** (Read et al., 2016)		**Test-retest TTS V:** ICC: 0.08 to 0.37 (Read et al., 2016) CV: 39.2 to 48.4% (Read et al., 2016) **Test-retest PVGRF** ICC: 0.59 to 0.75 (Read et al., 2016) CV: 9.5 to 10.1% (Read et al., 2016) **Test-retest time to PVGRF** ICC: 0.64 to 0.72 (Read et al., 2016) CV: 21.8 to 33.1% (Read et al., 2016)

Note: TTS = Time to stabilization; DPSI = Dynamic postural control index; PVGRF = Peak vertical ground reaction force; rPVGRF = Peak vertical ground reaction force normalized to body mass; rIMP = Landing impulse normalized to body mass; Time to PVGRF = time to peak vertical ground reaction force; Landing rPVGRF = rPVGRF in the landing phase of the drop-jump; Take-off rPVGRF = rPVGRF in the take-off phase of the drop-jump; Loading rate = Peak vertical ground reaction force (PVGRF) divided by time; LESS = Landing Error Scoring System; ICC = Intraclass correlation coefficient; SEM = Standard error of measurement; CV = Coefficient of variation; MDC = Minimal detectable change; TE = Typical Error.

Appendix IV. Reliability functional mobility tests

Test	Populations	Measurement(s)	Reliability
Squat movement competency screen (SMCS)	**Patients** (Edwards & Liberatore, 2018) **Male** (Edwards & Liberatore, 2018) **Female** (Edwards & Liberatore, 2018)	**Qualitative** Movement competency scale. Analysis of film from a frontal and sagittal view based on an overall impression of the movement and not based on segmental movement criteria. A 0 to 10-point scale with 10 being the best score (Edwards & Liberatore, 2018).	**Intra-rater reliability** Weighted kappa: 0.93 (Edwards & Liberatore, 2018) SE: 0.04 (Edwards & Liberatore, 2018) **Inter-rater reliability** Weighted kappa: 0.69 (Edwards & Liberatore, 2018) SE: 0.12 (Edwards & Liberatore, 2018)
Functional movement screen (FMS)	**Athletes** (Leeder, Horsley, & Herrington, 2016) **Recreational/healthy** (Bonazza et al., 2017; Everard, Harrison, & Lyons, 2017; P. A. Gribble, Brigle, et al., 2013; Kazman, Galecki, Lisman, Deuster, & O'Connor, 2014) **Male** (Bonazza et al., 2017; Everard et al., 2017; P. A. Gribble, Brigle, et al., 2013; Kazman et al., 2014; Leeder et al., 2016) **Female** (Bonazza et al., 2017; P. A. Gribble, Brigle, et al., 2013; Kazman et al., 2014; Leeder et al., 2016)	**Qualitative** Test specific criteria for each score has been defined and graded (0-3) (Cook et al., 2006a).	**Inter-rater** ICC: 0.81 to 0.91 (Bonazza et al., 2017; Cuchna et al., 2016; Leeder et al., 2016) **Intra-rater** ICC: 0.76 to 0.95 (Bonazza et al., 2017; Cuchna et al., 2016; P. A. Gribble, Brigle, et al., 2013)
		Quantitative Sagittal view of deep squat with video camera for joint movement analysis (i.e. Coaches Eye) and motion capture (i.e. Vicon).	**Test-retest Mocap** ICC ankle ROM: 0.63 (Krause et al., 2015) ICC knee ROM: 0.88 (Krause et al., 2015) ICC hip ROM: 0.62 (Krause et al., 2015) **Test-retest video application** ICC ankle ROM: 0.98 (Krause et al., 2015) ICC knee ROM: 0.98 (Krause et al., 2015) ICC hip ROM: 0.62 (Krause et al., 2015)
Selective functional movement assessment (SFMA)	**Recreational/healthy** (Dolbeer, Mason, Morris, Crowell, & Goss, 2017; Glaws et al., 2014) **Patients** (Dolbeer et al., 2017; Riebel, Crowell, Dolbeer, Szymanek, & Goss, 2017) **Male** (Dolbeer et al., 2017; Glaws et al., 2014; Riebel et al., 2017) **Female** (Dolbeer et al., 2017; Glaws et al., 2014; Riebel et al., 2017)	**Categorical** Each test categorized as follows: 1) functional non-painful, 2) functional-painful, 3) dysfunctional-non-painful and 4) dysfunctional painful (Glaws et al., 2014). **Criterion** 34-point criterion checklist that identifies if criteria are met (Glaws et al., 2014).	**Categorical intra-rater** Kappa: 0.72 to 0.83 (Glaws et al., 2014) **Categorical inter-rater** Kappa: 0.20 to 0.76 (Glaws et al., 2014) **Categorical inter-rater multi-segmental flexion** Kappa: 0.72 (Dolbeer et al., 2017) **Categorical inter-rater multi-segmental extension** Kappa: 0.68 (Dolbeer et al., 2017) **Categorical inter-rater multi-segmental rotation** Kappa: 0.37 to 0.73 (Dolbeer et al., 2017) **Categorical inter-rater deep squat** Kappa: 0.85 (Dolbeer et al., 2017) **Criterion intra-rater** ICC: 0.59 to 0.86 (Glaws et al., 2014) SEM: 1.2 to 2.2 (Glaws et al., 2014) MDC: 3.3 to 6.0 (Glaws et al., 2014) **Criterion Inter-rater** ICC: 0.43 to 0.72 (Dolbeer et al., 2017; Glaws et al., 2014) SEM: 2.0 to 2.7 (Dolbeer et al., 2017; Glaws et al., 2014) MDC: 5.4 to 7.5 (Dolbeer et al., 2017; Glaws et al., 2014)

Weight bearing lunge test (WBLT)	**Recreational/healthy** (Powden et al., 2015) **Patients** (Powden et al., 2015) **Male** (Powden et al., 2015) **Female** (Powden et al., 2015)	**Quantitative** Dorsiflexion: degrees (°) Distance to wall or other target: centimeters (cm)	**Inter-rater (goniometry and inclinometer)** ICC: 0.91 (Powden et al., 2015) MDC: 4.5° (Powden et al., 2015) **Intra-rater (goniometry and inclinometer)** ICC: 0.88 (Powden et al., 2015) MDC: 4.7° (Powden et al., 2015) **Inter-rater (distance)** ICC: 0.95 (Powden et al., 2015) MDC: 1.6 cm (Powden et al., 2015) **Intra-rater (distance)** ICC: 0.93 (Powden et al., 2015) MDC: 1.9 cm (Powden et al., 2015)

Note: ICC = Intraclass correlation coefficient; SEM = Standard error of measurement; CV = Coefficient of variation; MDC = Minimal detectable change.

Appendix V. HSEBT test description

Name	Stance foot	Starting position	Hand reaching	Direction	Measurement	Order
L SLS R45	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on P180 line angled toward R45. R hand on hip and trunk rotated in the direction of the reach.	L	R45	Maximum position of the middle finger (cm)	1
R SLS L45	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on P180 line angled toward L45. L hand on hip and trunk rotated in the direction of the reach.	R	L45	Maximum position of the middle finger (cm)	2
L SLS A0	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on R135 line angled toward A0.	B	A0	Maximum position of the middle fingers (cm)	3
L SLS A0	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on L135 line angled toward A0.	B	A0	Maximum position of the middle fingers (cm)	4
L SLS L45	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on R90 line angled toward L45. L hand on hip and trunk rotated in the direction of the reach.	R	L45	Maximum position of the middle finger (cm)	5
R SLS R45	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on L90 line angled toward R45. R hand on hip and trunk rotated in the direction of the reach.	L	R45	Maximum position of the middle finger (cm)	6
L SLS L90	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on R135 line angled toward A0.	B	L90	Maximum position of the middle fingers (cm)	7
R SLS R90	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on L135 line angled toward A0.	B	R90	Maximum position of the middle fingers (cm)	8
L SLS R90	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on L45 line angled toward A0.	B	R90	Maximum position of the middle fingers (cm)	9
R SLS L90	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on R45 line angled toward A0.	B	L90	Maximum position of the middle fingers (cm)	10
L SLS L135	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on R90 line angled toward R45. L hand on hip and trunk rotated in to the R45 direction.	R	L135	Maximum position of the middle finger (cm)	11
R SLS R135	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on L90 line angled toward L45. R hand on hip and trunk rotated in the L45 direction.	L	R135	Maximum position of the middle finger (cm)	12
L SLS P180	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on R45 line angled toward A0.	B	P180	Maximum position of the middle fingers (cm)	13
R SLS P180	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on L45 line angled toward A0.	B	P180	Maximum position of the middle fingers (cm)	14
L SLS R135	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on A0 line angled toward L45. R hand on hip and trunk rotated in the L45 direction.	L	R135	Maximum position of the middle finger (cm)	15
R SLS L135	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on A0 line angled toward R45. L hand on hip and trunk rotated in the R45 direction.	R	L135	Maximum position of the middle finger (cm)	16
L SLS RROT	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on R90 line angled toward A0 and allowed to rotate in direction of reach. Bilateral hands at shoulder height.	B	RROT	Maximum position of the middle finger (degrees)	17
R SLS LROT	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on L90 line angled toward A0 and allowed to rotate in direction of reach. Bilateral hands at shoulder height.	B	LROT	Maximum position of the middle finger (degrees)	18
L SLS LROT	L	L foot center of testing mat, R foot toe-touch between 20-30 cm radius on R90 line angled toward A0 and allowed to rotate in direction of reach. Bilateral hands at shoulder height.	B	LROT	Maximum position of the middle finger (degrees)	19
R SLS RROT	R	R foot center of testing mat, L foot toe-touch between 20-30 cm radius on L90 line angled toward A0 and allowed to rotate in direction of reach. Bilateral hands at shoulder height.	B	RROT	Maximum position of the middle finger (degrees)	20

Appendix VI. Approval letters from the Norwegian Centre for Research Data

Norsk samfunnsvitenskapelig datatjeneste AS
NORWEGIAN SOCIAL SCIENCE DATA SERVICES

Harald Hårfagres gate 29
N-5007 Bergen
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Ola Eriksrud
Seksjon for fysisk prestasjonsevne
Norges idrettshøgskole
Postboks 4014
0806 OSLO

Vår dato: 26.06.2013 Vår ref:34752 / 3 / AMS Deres dato: Deres ref:

TILBAKEMELDING PÅ MELDING OM BEHANDLING AV PERSONOPPLYSNINGER

Vi viser til melding om behandling av personopplysninger, mottatt 14.06.2013. Meldingen gjelder prosjektet:

34752	*Validation of Functional Mobility Screen*
Behandlingsansvarlig	*Norges idrettshøgskole, ved institusjonens øverste leder*
Daglig ansvarlig	*Ola Eriksrud*

Personvernombudet har vurdert prosjektet og finner at behandlingen av personopplysninger er meldepliktig i henhold til personopplysningsloven § 31. Behandlingen tilfredsstiller kravene i personopplysningsloven.

Personvernombudets vurdering forutsetter at prosjektet gjennomføres i tråd med opplysningene gitt i meldeskjemaet, korrespondanse med ombudet, ombudets kommentarer samt personopplysningsloven og helseregisterloven med forskrifter. Behandlingen av personopplysninger kan settes i gang.

Det gjøres oppmerksom på at det skal gis ny melding dersom behandlingen endres i forhold til de opplysninger som ligger til grunn for personvernombudets vurdering. Endringsmeldinger gis via et eget skjema http://www.nsd.uib.no/personvern/meldeplikt/skjema.html. Det skal også gis melding etter tre år dersom prosjektet fortsatt pågår. Meldinger skal skje skriftlig til ombudet.

Personvernombudet har lagt ut opplysninger om prosjektet i en offentlig database, http://pvo.nsd.no/prosjekt.

Personvernombudet vil ved prosjektets avslutning, 31.12.2013, rette en henvendelse angående status for behandlingen av personopplysninger.

Vennlig hilsen

Vigdis Namtvedt Kvalheim

Anne-Mette Somby

Anne-Mette Somby tlf: 55 58 24 10
Vedlegg: Prosjektvurdering

On 12/11/15 11:49, "Katrine Utaaker Segadal" <katrine.segadal@nsd.no>
wrote:

Hei,

Viser til mottatt meldeskjema for prosjektet 40996 "Inter-rater and intra-rater reliability of functional mobility screen".

Ved en feiltakelse ble det aldri sendt en skriftlig tilbakemelding på denne prosjektmeldingen fra oss. I følge meldeskjema skulle prosjektet avsluttes og data anonymiseres 20. juni 2015.

Kan du bekrefte at prosjektet er avsluttet og at det ikke lenger behandles personopplysninger i prosjektet?

--
Med vennlig hilsen/Kind regards

Katrine Utaaker Segadal
Seksjonsleder/Head of Section
+47 55 58 35 42 | +47 970 86 236

nsd.no | twitter.com/NSDdata

Norsk samfunnsvitenskapelig datatjeneste AS
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Ola Eriksrud
Seksjon for fysisk prestasjonsevne
Norges idrettshøgskole
Postboks 4014
0806 OSLO

Vår dato 28.01.2016	Vår ref: 40996/3/KS/LR	Deres dato:	Deres ref:

TILBAKEMELDING PÅ MELDESKJEMA

Vi viser til meldeskjema og senere korrespondanse angående prosjektet:

40996 *Inter-rater and intra-rater reliability of functional mobility screen*

Ved en inkurie ble det ikke gitt en skriftlig tilbakemelding på prosjektmeldingen. Veileder bekrefter per epost 29.12.2015 at prosjektet nå er avsluttet og datamaterialet anonymisert.

Personvernombudet avslutter derfor videre oppfølging av prosjektet.

Ta gjerne kontakt dersom noe er uklart.

Vennlig hilsen

Vigdis Namtvedt Kvalheim

Katrine Utaaker Segadal

Kopi: Stavros Litsos

Norsk samfunnsvitenskapelig datatjeneste AS
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Ola Eriksrud
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Postboks 4014
0806 OSLO

Vår dato: 03.12.2014 Vår ref: 40934 / 3 / LT Deres dato: Deres ref:

TILBAKEMELDING PÅ MELDING OM BEHANDLING AV PERSONOPPLYSNINGER

Vi viser til melding om behandling av personopplysninger, mottatt 26.11.2014. Meldingen gjelder prosjektet:

40934	*Påvirkning av mobilitet og styrke på prestasjon i overarmskast*
Behandlingsansvarlig	*Norges idrettshøgskole, ved institusjonens øverste leder*
Daglig ansvarlig	*Ola Eriksrud*
Student	*Fredrik Oksum Sæland*

Personvernombudet har vurdert prosjektet og finner at behandlingen av personopplysninger er meldepliktig i henhold til personopplysningsloven § 31. Behandlingen tilfredsstiller kravene i personopplysningsloven.

Personvernombudets vurdering forutsetter at prosjektet gjennomføres i tråd med opplysningene gitt i meldeskjemaet, korrespondanse med ombudet, ombudets kommentarer samt personopplysningsloven og helseregisterloven med forskrifter. Behandlingen av personopplysninger kan settes i gang.

Det gjøres oppmerksom på at det skal gis ny melding dersom behandlingen endres i forhold til de opplysninger som ligger til grunn for personvernombudets vurdering. Endringsmeldinger gis via et eget skjema, http://www.nsd.uib.no/personvern/meldeplikt/skjema.html. Det skal også gis melding etter tre år dersom prosjektet fortsatt pågår. Meldinger skal skje skriftlig til ombudet.

Personvernombudet har lagt ut opplysninger om prosjektet i en offentlig database, http://pvo.nsd.no/prosjekt.

Personvernombudet vil ved prosjektets avslutning, 31.12.2015, rette en henvendelse angående status for behandlingen av personopplysninger.

Vennlig hilsen

Katrine Utaaker Segadal

Lis Tenold

Kontaktperson: Lis Tenold tlf: 55 58 33 77
Vedlegg: Prosjektvurdering
Kopi: Fredrik Oksum Sæland fredriksaeland@gmail.com

Dokumentet er elektronisk produsert og godkjent ved NSDs rutiner for elektronisk godkjenning.

Norsk samfunnsvitenskapelig datatjeneste AS
NORWEGIAN SOCIAL SCIENCE DATA SERVICES

Harald Hårfagres gate 29
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Ola Eriksrud
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Vår dato: 03.02.2016 Vår ref: 47006 / 3 / MSS Deres dato: Deres ref:

TILBAKEMELDING PÅ MELDING OM BEHANDLING AV PERSONOPPLYSNINGER

Vi viser til melding om behandling av personopplysninger, mottatt 01.02.2016. Meldingen gjelder prosjektet:

47006	*Mobility of athletes participating in Youth Olympic Games*
Behandlingsansvarlig	*Norges idrettshøgskole, ved institusjonens øverste leder*
Daglig ansvarlig	*Ola Eriksrud*

Etter gjennomgang av opplysninger gitt i meldeskjemaet og øvrig dokumentasjon, finner vi at prosjektet ikke medfører meldeplikt eller konsesjonsplikt etter personopplysningslovens §§ 31 og 33.

Dersom prosjektopplegget endres i forhold til de opplysninger som ligger til grunn for vår vurdering, skal prosjektet meldes på nytt. Endringsmeldinger gis via et eget skjema, http://www.nsd.uib.no/personvern/meldeplikt/skjema.html.

Vedlagt følger vår begrunnelse for hvorfor prosjektet ikke er meldepliktig.

Vennlig hilsen

Katrine Utaaker Segadal

Marie Strand Schildmann

Kontaktperson: Marie Strand Schildmann tlf: 55 58 31 52
Vedlegg: Prosjektvurdering

Dokumentet er elektronisk produsert og godkjent ved NSDs rutiner for elektronisk godkjenning.

Personvernombudet for forskning

Prosjektvurdering - Kommentar

Prosjektnr: 47006

Vi kan ikke se at det behandles personopplysninger med elektroniske hjelpemidler, eller at det opprettes manuelt personregister som inneholder sensitive personopplysninger. Prosjektet vil dermed ikke omfattes av meldeplikten etter personopplysningsloven.

Det ligger til grunn for vår vurdering at alle opplysninger som behandles elektronisk i forbindelse med prosjektet er anonyme. Vi viser her til meldeskjema og bekreftelse fra daglig ansvarlig Ola Eriksrud per telefon den 03.02.2016 på at det ikke skal innhentes og registreres noen identifiserende opplysninger i forbindelse med prosjektet.

Daglig ansvarlig er gjort oppmerksom på at det foreliggende informasjonsskrivet må revideres slik at det fremgår helt eksplisitt at det ikke skal registreres personopplysninger om prosjektdeltakerne. Det må derfor også fremgå av skrivet at tilbakemeldinger om den enkelte idrettsutøverens score på mobilitet og balanse, gis umiddelbart etter testing.

Med anonyme opplysninger forstås opplysninger som ikke på noe vis kan identifisere enkeltpersoner i et datamateriale, verken:
-direkte via personentydige kjennetegn (som navn, personnummer, epostadresse el.)
-indirekte via kombinasjon av bakgrunnsvariabler (som bosted/institusjon, kjønn, alder osv.)
-via kode og koblingsnøkkel som viser til personopplysninger (f.eks. en navneliste)
-eller via gjenkjennelige ansikter e.l. på bilde eller videoopptak.

Vi gjør oppmerksom på at muntlig samtykke er like gyldig som skriftlig samtykke. Personvernombudet legger videre til grunn, dersom skriftlige samtykker likevel skal innhentes, at navn/samtykkeerklæringer ikke knyttes til opplysningene som registreres.

Appendix VII. Study IV: Warm-up procedures

The general part consisted of exercises and dynamic stretching as follows: 1) Jog (2 x 20 m), 2) lateral shuffle with focus on arm swings (abduction and adduction) (2 x 20 m), 3) angled shuffles forward and backwards (2 x 20 m), 4) jog with dominant arm shoulder roll forward and backwards (2 x 20 m), 5) skip with trunk rotation (2 x 20 m) and 6) skip with bilateral shoulder roll forward and backwards (2 x 20 m). The exercises were then repeated with the subject being instructed to slightly increase the intensity of the runs. These exercises took 4 minutes to complete.

Then dynamic stretches were performed, which consisted of three full body dynamic stretches in the sagittal, frontal and transverse planes: a total of six movements with a total of three repetitions per leg per movement. Specifically, the subjects started from a neutral stance position and assumed the following ending positions:

Sagittal plane

- Anterior stretch: Unilateral anterior step with bilateral hands posterior overhead reach.

- Posterior stretch: Unilateral posterior step with bilateral hands and foot/ankle reach.

Frontal plane

- Lateral stretch: Unilateral hip abduction step with opposite side bilateral hands overhead lateral reach.

- Lateral stretch: Unilateral hip adduction step with opposite side bilateral hands overhead lateral reach.

Transverse plane

- Hip external rotation: unilateral external rotation step with same side bilateral hands rotational reach at shoulder height.

- Hip internal rotation: Unilateral internal rotation step with same side bilateral hands rotational reach at shoulder height.

Appendix VIII. Marker set study I

Foot (6 markers):

- Right posterior calcaneus (RCA)
- Left posterior calcaneus (LCA)
- Right 5th metatarsal head (RVMH)
- Left 5th metatarsal head (LVMH)
- Right 1st metatarsal head (RFM1)
- Left 1st metatarsal head (LFM1)

Shank (12 markers):

- Clusters named from superior to inferior
    1. Right shank (RSK1, RSK2, RSK3, RSK4) - #1 proximal and anterior, #3 distal and anterior
    2. Left shank (LSK1, LSK2, LSK3, LSK4) - #1 proximal and anterior, #3 distal and anterior
- Right lateral malleolus (RFAL)
- Left lateral malleolus (LFAL)
- Right medial malleolus (RTAM)
- Left medial malleolus (LTAM)

Thigh (14 markers):

- Right greater trochanter (RFT)
- Left greater trochanter (LFT)
- Clusters named from superior to inferior
    3. Right thigh (RTH1, RTH2, RTH3, RTH4) - #1 proximal and anterior, #3 distal and anterior
    4. Left thigh (LTH1, LTH2, LTH3, LTH4) - #1 proximal and anterior, #3 distal and anterior
- Right lateral condyle (RFLE)
- Left lateral condyle (LFLE)
- Right medial condyle (RFME)

- Left medial condyle (LFME)

Pelvis (6 markers):

- Right anterior superior iliac spine (RIAS)
- Left anterior superior iliac spine (LIAS)
- Right posterior superior iliac spine (RIPS)
- Left posterior superior iliac spine (LIPS)
- Right lateral pelvis (RPEL)
- Left lateral pelvis (LPEL)

Thorax (4 markers):

- Spinous process C7 (CV7)
- Spinous process T10 (TV10)
- Superior jugular notch (SJN)
- Sternum xiphisternal joint (SXS)

Head (7 markers):

Based upon existing helmet in the lab and markers needed for the definition of the head segment the following are to be used:

- Right anterior head (RAH)
- Left anterior head (LAH)
- Right lateral head (RLH)
- Left lateral head (LLH)
- Right posterior head (RPH)
- Left posterior head (LPH)
- Aphex skull (SAS)

Upper arm segment (14 markers):

- Right acromion (RAC)
- Left acromion (LAC)
- Right rotation center shoulder joint (RSHO)
- Left rotation center shoulder joint (LSHO)

- Right humeral lateral epicondyle (RHLE)
- Left humeral lateral epicondyle (LHLE)
- Right humeral medial epicondyle (RHME)
- Left humeral medial epicondyle (LHME)
- Right upper arm (RUA1, RUA2, RUA3) - #1 proximal and anterior, #2 proximal and posterior
- Left upper arm (LUA1, LUA2, LUA3) - #1 proximal and anterior, #2 proximal and posterior

Lower arm segment (10 markers):

Segment coordinate system not calculated for hand reaches.

- Right radial styloid process (RRSP)
- Left radial styloid process (LRSP)
- Right ulnar styloid process (RUSP)
- Left ulnar styloid process (LUSP)
- Right lower arm (RLA1, RLA2, RLA3) - #1 proximal and anterior, #2 proximal and posterior
- Left lower arm (LLA1, LLA2, LLA3) - #1 proximal and anterior, #2 proximal and posterior

Hand (2 markers):

Segment coordinate system not calculated for hand reaches. Markers used to define position of max hand reach distance.

- Dorsal surface of the head right 5^{th} metacarpal (RHL5)
- Dorsal surface of the head left 5^{th} metacarpal (LHL5)

Appendix IX. Validation of the multiple linear regression of HSEBT outcome measurements

	Initial model (75%)				Validation model (25%)			
Test	***B***	**SE *B***	**B**	**R^2**	***B***	**SE *B***	**B**	**R^2**
R45 Step 1								
Constant	11.96	7.22						
Wingspan	.39	.041	.59***	.346				
R45 Step 2								
Constant	-3.93	8.45						
Wingspan	.47	.047	.62***					
Sex	3.07	.92	.24***	.388 (ΔR^2= .042)				
R45 Step 3					Forced entry			
Constant	.62	8.58			13.85	14.944		
Wingspan	.58	.069	.89***		.30	.14	.52*	
Sex	3.1	.90	.24***		2.27	1.73	.22	
Leg length	-.279	.12	-.22*	.407 (ΔR^2= .019)	.135	.242	.12	.288
L45 Step 1								
Constant	22.71	9.69						
Wingspan	.26	.055	.34***	.117				
L45 Step 2					Forced entry			
Constant	-3.86	11.13			13.00	17.11		
Wingspan	.40	.062	.53***		.32	.095	.50**	
Sex	5.15	1.21	.35***	.206 (ΔR^2= .089)	.93	2.02	.068	.215
L135 Step 1								
Constant	87,38	.83						
Activity level	-3.86	1.67	-.18*	.033				
L135 Step 2					Forced entry			
Constant	59.67	12.86			44.16	19.64		
Activity level	-4.64	1.69	-22**		-7.35	2.71	-.42**	
Leg length	.32	.15	.17*	.060 (ΔR^2=.027)	.49	.22	.34*	.134
R135					Forced entry			
Constant	64.68	1.08			66.07	1.69		
Activity level	-7.21	2.17	-.25**	.065	-14.20	3.17	-.53***	.28
RROT					Forced entry			
NE					NE			
LROT					Forced entry			
NE					NE			

Note: B = Unstandardized coefficient; β = Standardized beta coefficient; SE = Standard error; R^2 = Coefficient of determination; NE = No variables entered into the equation; R45 = Right anterolateral (45°) reach; R135 = Right posterolateral (135°) reach; L135 = Left posterolateral (135°) reach; L45 = Left anterolateral (45°) reach; RROT = Right rotational reach; LROT = Left rotational reach. Statistical significance denoted as: *p<.05, **p<.01 and ***p<.001.