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Validation of loaded Change of Direction tests using Robotic Resistance Technology

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Summary

Change of direction (CoD) is a fundamental part of field and team sports. It consist of an initial acceleration and deceleration into the a turn with a subsequent re-acceleration in another direction. A myriad of tests has been established in order to measure and analyze CoD, however, most of them is quantified by using time as their main outcome measure. Time tells us who was faster, however, it gives us little to no insight into what mechanics, techniques, phases is used by the “better” athlete. Robotic resistance device has been used in other sports such as sprinting and swimming, where it has been possible to quantify the performance in terms of time, velocity, acceleration, force and power. In order for this kind of depth analysis within CoD there needs to be a method to do so, and if there is to be a new method introduced, it needs to meet a validation criteria to prove itself. To date, three dimensional motion capture is the best option, however, there is issues with cost and the fact that there has to be access to a lab. Therefore, the aim of this to was to 1) develop a new protocols for the m505 test (180 degree turn) under loaded conditions using robotic resistance and 2) determine criterion related validity of continuous velocity measurement of an athlete performing m505 test with a robotic resistance device (ROB$_{vel}$), and compare it to established methods used for measuring center of mass (COM$_{vel}$ and COM$_{Pelvis\text{-}vel}$) in three-dimensional motion capture systems. Eight males and three females were recruited to the study. They were all playing at a moderate to elite level in their respective field based ball sport. The subjects were tested in the lab at the Norwegian School of Sports Sciences. A familiarization session with the test took place >48h before testing day. The testing itself took place over one day. The subjects were dotted up with reflective markers and attached via a belt to the robotic resistance device. They were then asked to perform m505 tests, two on each leg, with all three different loads, 3, 6 and 9kg. The main outcome variable was velocity at the given time interval for the test. The ROB$_{vel}$ data was synchronized to the three dimensional motion capture data (CAR$_{vel}$, COMpelvis$_{\text{-}vel}$, COM$_{vel}$) and compared using cross correlation analysis which showed strong correlations between the robotic resistance device compared to three dimensional motion capture ROB to CAR (r=.99), ROB and COM$_{pelvis}$ (r=.96) and ROB and COM (r=.94). An unpaired t-test was used to determine the differences between the methods, and it showed that there was no significant difference for all three loads. Bland Altman figures show little to no bias between ROB compared to kinematic data. When looking at the results, it is possible to say that this method met the validation criteria for quantitative testing, and therefore it is a valid method to test and analyze CoD performance in field based sports for both males and females. The use of robotic resistance device can give coaches a more portable and cost effective way to train, test and analyze their athletes, in addition, it can give them valuable insight into what their athletes need to work on.

Prologue

This has been a great opportunity to work with something I am truly passionate about, not only because I am myself a ball sport athlete who could have benefitted from this study. Additionally, due to the measurement techniques used in study is something I plan to work with after the project is finished. It has been a year of learning, struggles, delays and joy.

I am very thankful to all of the subjects that took their time and performed this study. You were all engaged and wanted to learn about not only your own performance, but also the techniques that goes into measuring COD performance.

A massive thank you to my supervisor Ola Eriksrud, without whom I would never been introduced to this project. It's been a pleasure to watch and work with someone at the highest level of biomechanical analysis. Additionally, thank you for the supervision during the writing part and the feedback you've given. I am so very grateful I got to be a part of this.

Thank you to Øyvind Gløersen, who helped with analyzing the biomechanical data, helped fixing the cameras via FaceTime when you were not around, and for always being there when things didn't work in the lab. You're the main reason the lab runs so smoothly.

I want to thank my good friend and professor Sajad Bhat who convinced me to not start my master's degree straight after my bachelor's degree, but to work and see if this line of work is something I want to be a part of. I grew during my 1,5 years away university and it made me more prepared and hungry for when I actually started my master's degree.

I would also like to thank my bosses Kristin Eide and Charlotte Gundersen, who have understood the importance of this project to me and let me put it in front of work and letting me work my own way. Your support has been vital and I am very grateful for it.

Lastly, I want to thank my family and my girlfriend Yvonne. You guys' support have been the most important and uplifting throughout this whole adventure. Delay after delay, you guys gave me encouragement and told me to keep my head down and just work. Thank you!

Fredrik Andreas Ahlbeck

NIH, May, 2021

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1.0 Theory

1.1 Change of Direction in individual and team sports

Change of direction (CoD), “skills and abilities needed to change movement direction, velocity, or modes” (DeWeese & Nimphius, 2016) is one component of agility and is fundamental to field and team sports performance such as tennis, Australian Football Rules (AFL), soccer and basketball (Sheppard & Young, 2006). In soccer talent identification CoD is the prominent factor for predicting player selection and distinguishing between elite and sub-elite players. In American football CoD is the most important factor during the draft to predict a players drafting status (wide receivers, running backs, defensive backs and quarterbacks) (Brughelli, Cronin, Levin, & Chaouachi, 2008).

In team and individual sports there are a number of movements happening in horizontal plane during competition. For instance, in AFL, players’ movements during a game can be described as horizontal, intermediate (walking, jogging) with short high-intensity spouts, with on average 150 short sprints and runs lasting < 6 seconds per game (Wisbey, Montgomery, Pyne, & Rattray, 2010). Similar estimates have been found in elite-soccer players where approximately 80-90% consists low to moderate intensity runs and 10-20% consists of high intensity turns, sprints and rapid explosive movements, including directional change, and a majority of them are in the horizontal plane. Additionally, different positions on the field propose different directional change demands during a game, for instance, a striker performed more maximal sprints compared to midfielders and defenders. Furthermore, defenders performed more high intensity shuffling and backwards movements compared to the midfielders and striker (Bloomfield, Polman, & O'Donoghue, 2007). In basketball, players are routinely moving several kilometers, performing many high speed movements forward and lateral directions combined with decelerations and short sprints. In addition to 50 explosive vertical jumps per game (Montgomery, Pyne, & Minahan, 2010). Individual high level tennis players average 4 directional changes per point and is on average performed every 4 meters. Additionally, most of these directional changes occur within a tennis player’s “comfort zone” which refers to 3m in which the player can reach. Furthermore, the majority of movements in tennis are performed laterally (71%) compared to anteriorly (>20%) and posteriorly (>8%) respectively (Filipčič, Leskošek, Munivrana, Ochiana, & Filipčič, 2017).

1.1.1 What is Change of Direction?

A change of direction in the horizontal plane in it's simplest form, assuming starting from standing still, consist of an initial acceleration and deceleration into a turn with a subsequent re-acceleration. These events have previously been dissected into three different steps: i) a deceleration step (penultimate foot contact), ii) a plant step (redirecting the players center of mass), iii) the final step is a propulsion step which is re-accelerating the player in to opposite direction (Clarke, Mundy, Aspe, Sargent, & Hughes, 2018). For the purpose of this study the initial acceleration and deceleration phase is defined as Phase 1, the re-acceleration phase is defined as Phase 2 (see figure 1 and 2 below). Change of direction has been assessed extensively in vertical movements, such as countermovement jump, where similar phases are defined (Sole, Mizuguchi, Sato, Moir, & Stone, 2018). Such vertical assessments have been done under both unloaded and loaded conditions with great success in field sports in order to assess player's sprint, jump, change of direction ability (Kobal, Pereira, Zanetti, Ramirez-Campillo, & Loturco, 2017). Similar plyometric training programs under unloaded and loaded conditions have been used horizontally with soccer players that resulted in similar improved results (Negra et al., 2019).

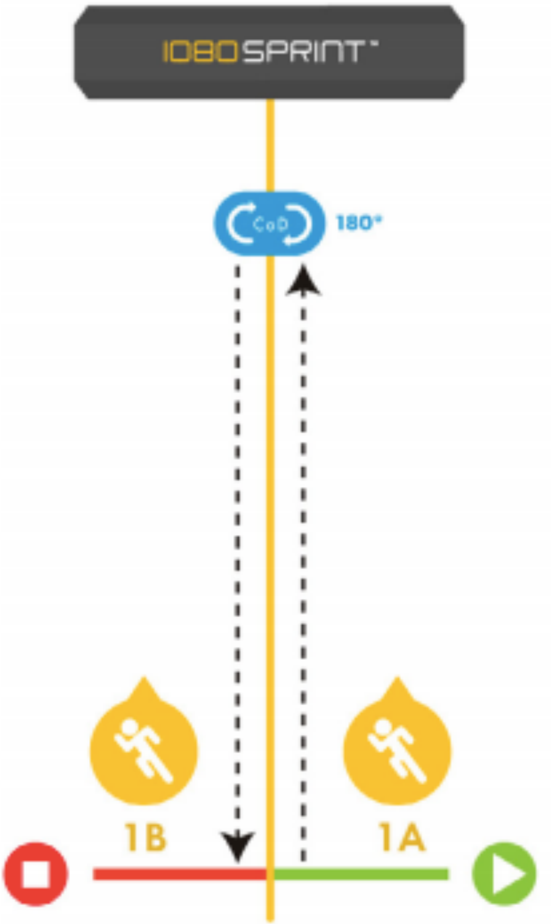


Figure 1: *Visual display of different phases (1080 Motion AB, Stockholm, Sweden).*

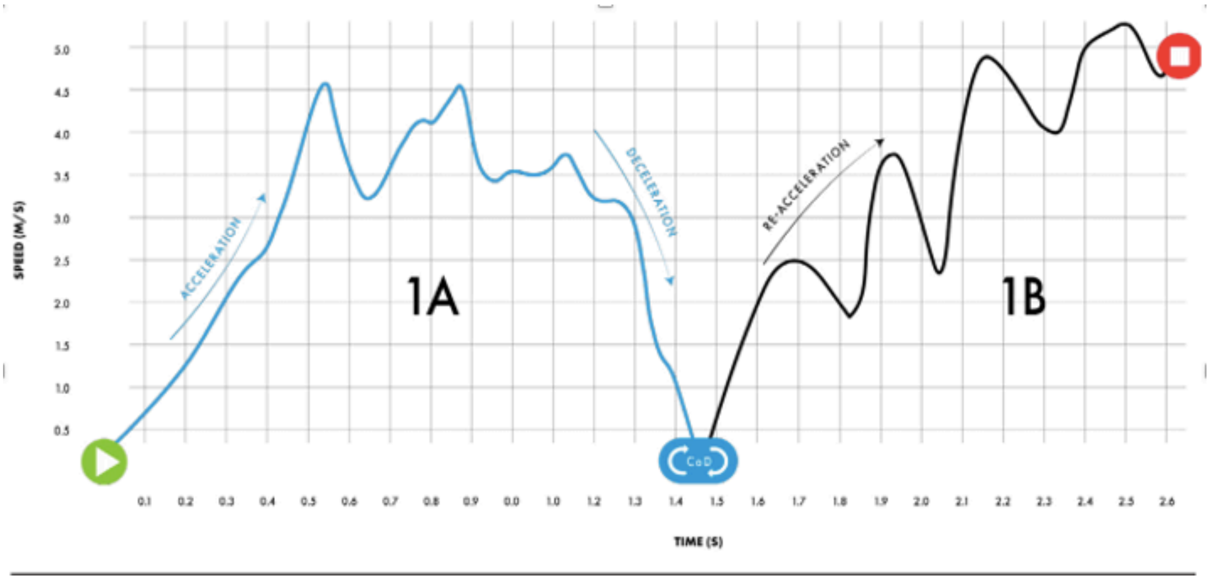


Figure 2: *Phase description displaying development of speed as a function of time. (1080 Motion AB, Stockholm, Sweden).*

1.1.2 Physical demands in Change of Direction

Deceleration or braking is the first part of the directional change. It involves absorbing the momentum or force placed on the body (Harper., 2019). While acceleration puts metabolic demands on the body, the deceleration has a higher mechanical load (Harper, Carling, & Kiely, 2019). Furthermore, studies show that elite players are capable of maintaining a higher frequency and magnitude of accelerations and decelerations compared to players at a lower level. In addition, there is a decline in the frequency of these movements in the second half of a competitive game, suggesting fatigue plays a major part in the acceleration/deceleration (Harper et al., 2019). The main finding of their study was that with the exception of American football, all players have a higher frequency and intensity of decelerations compared to accelerations during a game. To conclude their meta analysis, Harper et al., (2019) states the importance of the measures of external biomechanical loads during team sports. Furthermore, states the importance to practitioners involved to make sure the athletes are optimally prepared for the high biomechanical loads put on them in acceleration and deceleration situations during a competitive game.

There is a lack of established criteria for how to measure CoD that has led to little consensus on what specific muscle/muscle group is responsible for a good executed directional change. However, there are findings suggesting a correlation between eccentric knee flexor strength and CoD. Additionally, this provides the ability to discriminate differences in CoD in elite and sub-elite athletes (Chaouachi et al., 2012). Furthermore, the approach velocity during deceleration phase prior to a 180 degree directional change correlate with eccentric knee flexor peak torque in elite soccer athletes compared to novice (Jones, Thomas, Dos'Santos, McMahon, & Graham-Smith, 2017).

1.1.2 Assessing Change of Direction

Currently a myriad of different tests are used to assess CoD performance (Nimphius, Callaghan, Bezodis, & Lockie, 2017) and grouped based on duration (short < 6 seconds; long > 6 seconds) (R. G. Lockie, Post, & Dawes, 2019) or number of changes of direction (Nimphius et al., 2017) with the primary outcome variable being overall time. Since tests have different durations with different numbers of short sprints and changes of directions, it is not only difficult to compare results between tests, but also to determine which physical quality assessed. Specifically, duration and number of short sprints are two concerns with longer tests as their results are more representative of sprinting and anaerobic endurance capacity rather than change of direction (Nimphius et al., 2017). This becomes problematic as linear sprinting is considered not to transfer to change of direction performance and to be a different athletic quality (W. B. Young, McDowell, & Scarlett, 2001). However, others have reported findings to the contrary (Gabbett, Kelly, & Sheppard, 2008). Regardless, tests should assess what occurs during the different phases of change of direction as they represent different physical qualities such as eccentric (phase 1) and concentric strength (phase 2) as well as technical execution. Such information can provide coaches with important information about what to target in subsequent training programs. However, if anaerobic capacity is to be assessed longer tests are certainly indicated.

Consequently, shorter tests have the advantage of quantifying change of direction as an athletic quality as fewer sprints and one change of direction performance is done. This provide the opportunity to explore initial acceleration and deceleration to re-acceleration. One such test is the modified 505, which consist of two five meter sprints with one change of direction (180 degrees). Even such short test are critizised as linear sprint ability can mask change of direction ability. Since linear sprints and change of direction represent different athletic qualities attempts to mitigate these shortcomings have been done. Change of direction deficit is one example where the difference in time between the 505 test and a 10 m linear sprint is calculated to quantify the cost (time) of performing one change of direction (find ref from Nimphius 2016 here). However, information of how the athlete performed the initial acceleration to deceleration and the re-acceleration phase cannot be obtained from change of direction deficit. In fact, such information based on current testing procedures is currently unknown. This is important in field based testing considering that entry speed has been shown to influence the 505 tests based on comparisons of the two versions; 1) original (15 m run-up) and 2) modified (5 m run-up) to the turn. Measurements from the original test could only explain 53% of the variance in the modified test (Gabbett et al., 2008). As the speed into the change of direction is the only difference between these two tests it becomes apparent that entry speed should be monitored and documented. Furthermore, the willingness to assume a greater speed in the initial acceleration and deceleration phase might be an indicator of the eccentric capacity of the athlete (Nimphius, 2013). Simple measurements of time and speed during this phase would be helpful in this regards. However, the 505 test in its current form does not quantify phase specific variables such as time, speed and acceleration, but rather overall time. Thus, how the athlete performed in the different phases is unknown. In order to do that different technologies that can measure of how athlete moves, such as the center of mass (COM), during the test is needed. Currently, different technologies have been used to obtain phase specific information (i.e. time, velocity and acceleration) such as motion capture. Motion capture is a great tool to measure CoD ability if there is access to a lab, for most practitioners it is not. The cost and time is to great. In addition, laser timing systems equipment has been used, which have been scrutinized for masking actual CoD ability. Furthermore, these mechanisms have instead measured aerobic ability and linear sprinting rather than CoD ability. (K. Hader, D. Palazzi, & M. Buchheit, 2015; Nimphius et al., 2017; Spiteri, Cochrane, Hart, Haff, & Nimphius, 2013).

The importance of change of direction in sports have been mentioned prior (Nimphius et al., 2017). It is increasingly clear in field sports, such as soccer where a player makes on average 700 turns, in a variety of angles during a game (Robert G. Lockie, Schultz, Callaghan, Jeffriess, & Berry, 2013). Additionally, in these sports there are a variety of physical demands that the athletes have to perform depending on the sport and position (Bloomfield et al., 2007). For instance, a basketball player performing a "step-back" move will not move in a perfect 180-degree angle (Montgomery et al., 2010). Furthermore, this leads to huge limitations to the 505-test as it consists solely of a single 180-degree turn.

As change of directions in different individual and team field sports occur in directions beyond the 180 degrees the 505 test might lack content validity. Especially considering that CoD performance is angle dependent (Brughelli et al., 2008; Sheppard & Young, 2006). Thus, short tests should with different CoD angle turns with quantification of the different phases should be explored as done by Hader and Buchheit (2015). Specifically, they developed a CoD tests for soccer consisting of CoD at angles of 0, 45 and 90 degrees to target the lack of content validity and thereby improve external or ecological validity (Karim Hader, Dino Palazzi, & Martin Buchheit, 2015). Technically, the 505 test can be modified to consist of not only a 180, but different angular turns such as 90 or 135 degree turns.

The lack of simple tests that quantify the CoD capacity that provide phase specific information at different angles might be one reason why coaches resort to traditional strength and plyometric tests to target this quality. Even if CoD is dictated by the capacity to decelerate and accelerate COM horizontally through repetitive unilateral actions of the lower extremities vertical bilateral and unilateral tests and training interventions are used extensively to target CoD capacity. Thus, based on the principle of specificity it might not be surprising that vertical strength and power in bilateral (Brughelli et al., 2008; R. G. Lockie, Dawes, & Jones, 2018; W.B. Young, Hawken, & McDonald, 1996) and unilateral exercises (Marcovic, 2007; Negrete & Brophy, 2000; Peterson, Alvar, & Rhea, 2006Brughelli, 2008 #540; W. B. Young, James, & Montgomery, 2002) have a variable relationship to CoD performance. However, reactive strength in bilateral (Djevalikian, 1993; W.B. Young et al., 1996; W. B. Young et al., 2002) and unilateral vertical exercises (ex; drop jump) (W. B. Young et al., 2002) have a stronger relationship to CoD performance than vertical strength and power exercises. Therefore, it might not be surprising that training studies targeting vertical exercises (Jullien et al., 2008; McBride, Triplett-McBride, Davie, & Newton, 2002; Thomas, French, & Hayes, 2009; Tricoli, Lamas, Carnevale, & Ugrinowitsch, 2005) have shown variable results in improving CoD ability. In a recent meta-analysis (Asadi, Arazi, Young, & de Villarreal, 2016) reported that the best results from plyometric training was observed when the horizontal and unilateral exercises were targeted. These results might not be surprising when one considers the principle of specificity concerning the direction of force application into the ground. Based on research on linear sprint we know that the ability to generate horizontal force is a predictor of performance (Hunter, Marshall, & McNair, 2005).

Based on the flaws of the tests described above. There is a new for a method to measure the continuous movement of the athlete’s change of direction movement. Tests that describe how center of mass and center of mass velocity has been requested (Nimphius., 2017). At the time of this writing, no such method exists.

1.2 Validation Criteria in new testing method

In order for a new method to be used or classified as the new “Gold standard” there are certain criteria that has to be met. This process is not just for introducing a testing method, it is used whenever a new software, piece of equipment or instruments are introduced. These standards make sure that the method is objectively works for its intended purpose (Nata, 2013). In the case of validating a method previously used, the facility needs to be able to achieve the published results under their own testing conditions.

Comparative validation is defined as the correlation or cross testing between two or more methods, where the certified method serves as a reference to the new method being tested. As of now there is no set numerical standard for comparative validation, generally the method with the most accuracy and sensitivity is the best one (Nata, 2013). Sensitivity relates to the method having very low variation in testing and therefore lesser measurement uncertainty. Accuracy is mostly used in terms of reproducibility or repeatability and is therefore not a criteria for validation, however, it describes how close the measurement is to the true value (trueness is often described as bias), and precision (Nata, 2013).

To summarize, the following should be considered when performing method validation:

- Sensitivity – (Described above)
- Measuring interval (Definition of acceptable interval in which testing can have acceptable level of uncertainty)
- Trueness – (Bias)
- Precision/accuracy – (Described above)
- Ruggedness – (measure of robustness. An expression of to what degree results are effected by minor changes from the experimental method)
- Measurement uncertainty – (expression of the statistical spread of values to a measurement)

(Nata, 2013).

1.3 Improving Change of Direction

Since horizontal plyometric exercises appear to have a good effect on CoD performance, it might be that strength training programs that target horizontal movements also might be beneficial. In soccer there has long been studies looking at loaded and unloaded jumps and sprints in order to increase players' horizontal and vertical explosive movements on the pitch. Evidence of increased vertical and horizontal power, velocity and jumping ability in female and male soccer players, both at an elite and non-elite level have been found using training programs implementing loaded conditions (Kobal et al., 2017). In order to determine if force or speed is to be targeted by a training program force-velocity relationships have been used to determine training programs that targeted vertical jumping

(Samozino, Rejc, Di Prampero, Belli, & Morin, 2012). With the recent development and application of robotic resistance technology such as the 1080 Sprint (1080 Motion Nordic AB, Lidingö, Sweden) (Cross. M, Lahti. J, Brown. S, Chedati. M, Jimenez-Reyes. P, Samozino. P, Eriksrud. O, Morin. J, 2018) such profiles can be generated for different CoD tests as well. Such force-velocity profiles might provide coaches with the necessary information to determine if strength or speed should be the targeted in CoD training program. Using a belt or a vest attached to the device, the 1080 sprint has been used previously to target resisted and assisted sprinting while measuring continuous data (Cross, Samozino, Brown, & Morin, 2018) . Furthermore, this offers the advantage of adding external loads for training, as well as CoD testing during loaded conditions. Additionally, it allows us to quantify the different phases of the CoD under these loaded conditions. Furthermore, this might allow us the generate force and load velocity profiles that subsequently can be used to determine how to target training and document change. With the addition of robotic resistance device to test CoD ability, there is a need for development of a new protocol specifically for speed and resistance settings, as this has never been done before as the writing of this study.

Using the Sprint 1080 with continuous velocity measurements offers insights into details of the acceleration, deceleration and re-acceleration. A study investigating the reliability of deceleration kinetic and kinematic variables in a group of athletic sports students using radar (Harper, Morin, Carling, & Kiely, 2020). By measuring the mass of the subjects in addition to radar data they were able to calculate the following variables with good precision:

Kinematic:

- Vmax (m/s) – Maximum velocity
- TT50% Vmax (s) – 50% of maximum velocity
- TTS (s) – Time to stop
- DTS (m) – Distance to stop
- DEC_{ave} (m/s^2) – Average deceleration
- E-DEC_{ave} (m/s^2) – Average early deceleration
- L- DEC_{ave} (m/s^2) – Average late deceleration
- DEC_{max} (m/s^2) – Maximum deceleration
- $TIIDEC_{max}$ (s) – Time to maximum deceleration

Kinetic

- HBF_{avg} (N) – Average breaking force

- E-HBF_{avg} (N) – Average early breaking force
- L-HBF_{ave} (N) – Average late breaking force
- HBP_{ave} (W) – Average breaking power
- E-HBP_{ave} (W) – Average early breaking power
- L-HBP_{ave} (W) – Average late breaking power
- HBI_{ave} (N/s) – Average breaking impulse
- E- HBI_{ave} (N/s) – Average early breaking impulse
- L- HBI_{ave} (N/s) – Average late breaking impulse
- HBF_{max} (N) – Maximum breaking force
- HBP_{max} (W) – Maximum breaking power
- HBI_{max} (N/s) – Maximum breaking impulse

(Harper et al., 2020)

Now imagine a device that is able to measure more all of these variables, in addition to acceleration data, with different loads and speeds, in real time. Imagine the details at which CoD could be broken down to and analyzed. This could have a massive impact on how we asses and measure CoD.

Summary

Phase specific information about the initial acceleration, deceleration and re-acceleration phases of the 505 test will provide coaches with both lab and field based approach that would give important information concerning CoD performance. With the use of robotic resistance technology information about the COM movement (i.e velocity and acceleration) during these phases is possible. Furthermore, how the 505 test is performed under loaded conditions using robotic resistance might provide even more information as to what coaches should target in their subsequent training programs to improve CoD performance.

1.4 Aim of the study

The purpose to this project is to 1) develop a new protocols for the 505 test (180 degree turn) under loaded conditions (3, 6 and 9 kg) using robotic resistance and 2) determine criterion related validity of continuous velocity measurement of an athlete performing 505 test with a robotic resistance device (ROB_{vel}), and compare it to established methods used for measuring center of mass (COM_{vel} and $\text{COM}_{\text{Pelvis-vel}}$) in three-dimensional motion capture systems.

Test development:

The original 505 test is described in detail elsewhere (Draper & Lancaster, 1985) and consist of one 180 degree turn. The modifications added in the current study is that CoD not only occur at 180 degree turns. The original 505-test consists of 10 meters of total running, 5 meters run to a directional change at 180 degrees and finally a 5 meter run the opposite direction. The test involves an acceleration phase, followed by a deceleration phase as the participant goes into the directional change, and finishes with a re-acceleration phase (Draper & Lancaster, 1985). Modifications to this test with the use of robotic resistance technology was developed by Fredrik Ahlbeck (master's student) and Ola Eriksrud, PhD.

Equipment:

Robotic resistance

For measuring and loading a robotic device called 1080 Sprint (1080 Motion AB, Stockholm, Sweden) was used. It is a portable developed to measure sprinting, change of direction and swimming. A 80m line is used to measure performance variables, such as velocity, acceleration, force and power. In addition, tt provides resistance and assistance to the athlete during the 505 tests. Both control of resistance and speed settings as well as outcome measurements (position, time and pulling force) are adjusted and obtained at 333 Hz. Outcome variables are then used to calculate speed, acceleration and power.

As a part of this project software developments were made. Specifically, change of direction templates were developed as follows:

1. Start of measurement defined as when recorded velocity increased above 0.2 m/s. This has been applied to linear sprint testing and training (Rakovic., 2020)
2. Change of direction was defined as when the velocity of the recording in the 1080 Sprint changed direction.
3. Test divided into two phases:
    a. 1a: initial acceleration to deceleration defined based on distance from start to change of direction
    b. 1b: same distance as for 1a

4. Outcome variables (overall and phase specific)
    a. Time (s)
    b. Distance (m)
    c. Peak and average velocity (m/s)
    d. Peak and average acceleration (m/s^2)
    e. Peak and average pulling force (N)
    f. Peak and average pulling power (W)

The different loads used were 3, 6 and 9kg, assisted and resisted. Speed settings were set to 14 m/s (assisted) and 6 m/s (resisted). Resistance mode was set to ballistic

Belt and swivel

A belt was used to attach the cable from the 1080 Sprint to the subject. A thin rope with 2 carabiners and a pulley is attached to the belt to avoid friction while changing direction. Spefically, this was attached both in front and the back of the left hip when turning off the right foot and vice verse. The belt was situated at the hip, this to ensure that force anchor is as close as possible to their center of mass.

Adjustable robotic stand

An adjustable stand was used to provide stability and provide the ability to adjust the height of the resistance be in parallel with the hip of the subject, with minimal friction.

Protocol:

Testing order

Prior to any testing, every subject performed a standardized warm-up (see appendix I). Thereafter the subjects were tested in a set order of the following tests:

- 3kg resistance – 180 degree turns (2 trials on each leg)
- 9kg resistance – 180 degree turns (2 trials on each leg)
- 6kg resistance – 180 degree turns (2 trials on each leg)

All subjects started with turns off the left and then the right leg for all loaded conditions (see table 2.3).

2.0 Method

2.1. Subjects

For this study, eight males (age: 22±4.2 years; weight: 83.3±17kg; height: 181.6±12.7 cm) and three females (age: 21.7±1.5 years; weight: 69.7±2.5kg; height: 167±3.6 cm) were recruited. The inclusion criteria required them to have experience with a field based ball sport. The following sports were included in this study; soccer (n=3), basketball (n=4) and handball (n=3), and floorball (n=1). They had to be physically healthy and perform multiple strenuous direction changes. Any participant with a lower extremity injury at the time of testing and/or six months prior to initiation of testing were excluded. The study was approved by the local Ethical committee and the National Data Protection Agency for Research (ref number: 148213), and conducted in accordance with the Declaration of Helsinki. Prior to participation all subjects, provided a written informed consent after being given detailed verbal and written explanation of the purpose, procedures and risks associated with participation.

2.2 Experimental Design

The study was conducted in the biomechanical labs at the facilities at the Norwegian School of Sport Sciences. The testing was done in January and February of 2020. The data collection of each subject took place in 1 day.

2.2.1 Familiarization

All subjects had a first session to familiarize with the testing protocol. Which is recommended when doing the 505-test (Barber, Thomas, Jones, McMahon, & Comfort, 2016). The subjects started off with the standardized warm-up protocol (See appendix 1). After, the subjects performed all the tests with the robotic resistance device under loaded conditions (See table 2.3 for test order).

2.3 Testing Procedure

After the standardized warm up (Appendix I), the subjects performed the 505-test in a randomized order (see table 2.3). Each test was done with a different robotic resistance; 3, 6 and 9kg. The resistance was done using a belt connected to 1080 Sprint (1080 Motion AB, Stockholm, Sweden), set up to a rig to adjust for hip height (see figure 4 for testing set up). Two trials were done on each leg at a time before changing (left first, then right), with the three different loads making it a total of 12 trials, therefore, there was a 2-minute rest in-between each trial. Each trial is timed in order to compare the times to other studies investigated 505-test and used time as their dependent variable.

Total running distance (10m) was consistent for all 505 tests. All tests had the same starting point (marked with sports tape on the floor). As second CoD point (marked with sports tape on the floor) was located at a 5 m distance from the starting point and 0.3 m in front of the pulley system and parallel to the line of pull from 1080 Sprint (Figure 3). From the starting point the subject was instructed to sprint as fast as possible and then change direction at the CoD point. This initial phase of the 505 test is defined as the acceleration and deceleration phase (phase 1a). At the CoD point the subject executed a 180-degree CoD before re-accelerating to the different endpoints located 5 m away from the CoD point along the defined angulation. This phase was defined as the re-acceleration phase (phase 1b).

Based on practical experience and published data on the 505 test the load protocol outlined in Table 2.2 was used. Consequently, assisted speed was set to a greater value. The maximum resisted speed was set to 14 m/s, as this is the default setting on 1080 Sprint and one does not want an imposed speed restriction during phase 2. Furthermore, in order to develop load and force-velocity profiles similar to what has been done for linear sprinting (Cross, Samozino, Brown, & Morin, 2018) multiple loads were tested. Based on clinical experience loads of 3, 6 and 9 kg were used. Furthermore, the resistance mode used were No flying weight as it provides inertia with positive acceleration and isotonic resistance with an acceleration <0 m/s^2.

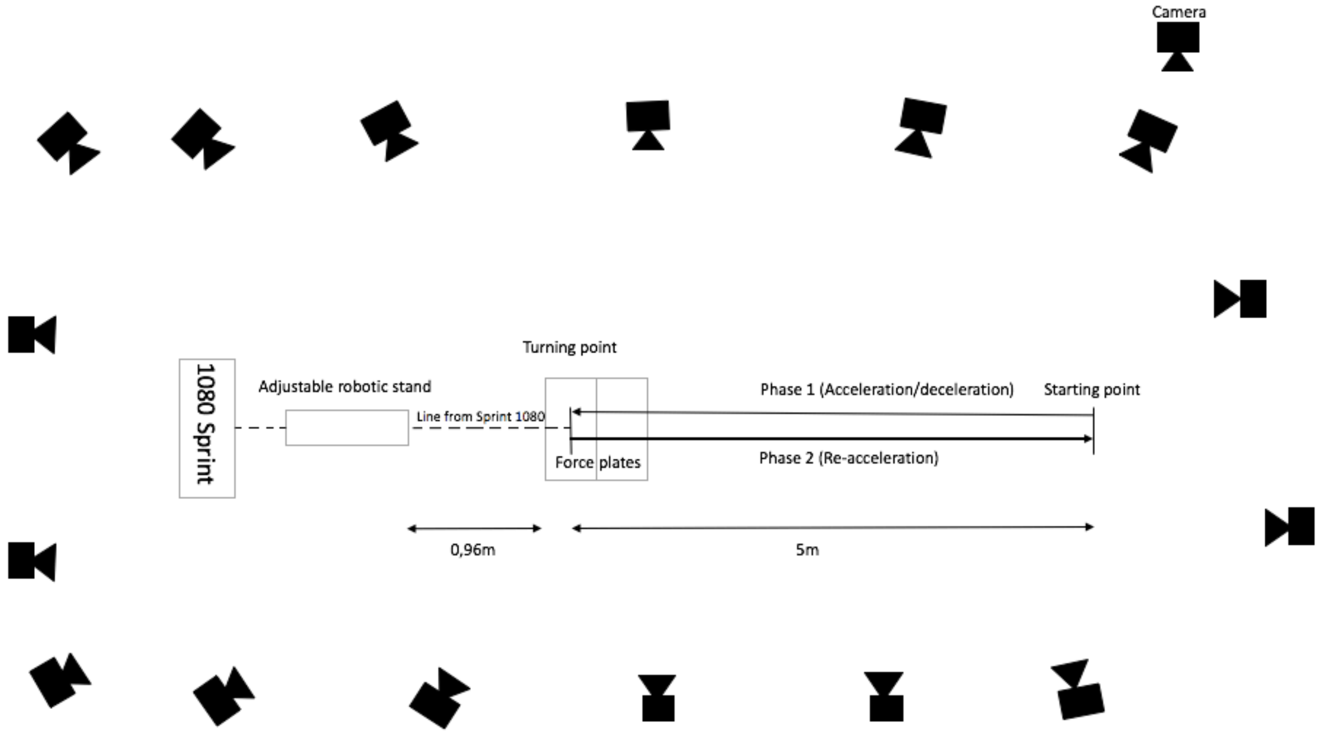


Figure 3*. Schematic overview of directional modifications of the 505 test using robotic resistance technology system.*

The testing order was designed with the specific purpose to keep the subjects in the dark on what type of turn and what weight they were going to do next, and therefore decrease the chances of the order influencing the results.

Table 2.2. Test protocol

Directional Change (Degrees)	Resistance (kg)	Leg (2 on each)	Reps	Rest
180	3kg	Left	2	2 minutes
180	3kg	Right	2	2 minutes
180	9kg	Left	2	2 minutes
180	9kg	Right	2	2 minutes
180	6kg	Left	2	2 minutes
180	6kg	Right	2	2 minutes

2.4. Kinematic calculations

75 reflecting markers were placed all over the body to analyze the movement in three-dimensional motion capture. It included 6 markers on the feet, 10 on shank, 10 on thigh segment, 6 pelvis, 6 thorax, 4 head markers, 14 upper arm, 10 lower arm, 2 hand, 5 markers on the sprint 1080, 5 on the adjustable hip stand and 1 on the carabine (for details see appendix III).

2.5 Equipment

Robotic resistance

1080 Sprint (1080 Motion AB, Stockholm, Sweden) was used to provide resistance and assistance to the different 505 tests. Described in more detail in Test development.

Belt

The belt was used an attachment point between the athlete and the robotic resistance device. This is described in Test development.

Adjustable robotic stand

The main purpose of the adjustable stand was to provide stability and the ability to adjust the height to be at hip height of the subject.

Motion capture

Both kinetic and kinematic variables were obtained. Specifically, kinematic variables were obtained using (Qualisys Oqus 400 cameras, Qualisys AB, Gothenburg, Sweden). 16 cameras were set in different vertical positions (wall and tripods) to ensure that they could capture markers in anterior and posterior positions on the body positions while performing the different CoD tests (Figure 3). Recording frequency will be set to 240 Hz. Prior to data acquisition standard calibration was performed (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 fail calibration as identified 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 millimeters); and 3) if the T-shaped wand was subjectively judged to have not adequately covered the recording volume (approximately 6 m in length and width and 2 m height). Body markers are identified in Appendix V.

Three-dimensional kinetic data was obtained using floor-mounted force plates (AMTI, Watertown, MA, USA). Specifically, they determined three-dimensional forces at the point of change of direction for all tests. Data from the 1080 Sprint to motion capture data (kinetic and kinematic variables) was synchronized to when the pull of the line and COM movement is > 0,2 m/s.

Figure 4: *Testing set up.*

3.6. Data analysis

Marker data was identified using Qualisys Track Manager. The marker locations were established using two separate static position holds as calibration, one standing in anatomical position and a second with flexed elbows, palms of the hand facing down. From there segments were for each body part including; foot, shank, thigh, pelvis, thorax, upper arm, lower arm, hand and head. These were all done according to the recommendations from the International Society of Biomechanics (Wu, et al,. 2002). The marker data and the full-body kinetic model was exported to Visual 3D (C-motion, Germantown, MD, USA) where overall center of mass (COM) and pelvis (COM_{pelvis}) was calculated. From there the velocity of carabine marker (CAR) was calculated (CAR_{vel}), as well as velocities for COM (COM_{vel}) and COM_{pelvis} ($COM_{pelvis\text{-}vel}$). The set up and calibration in the lab was made to ensure the subjects performed their horizontal movement along the y-axis, therefore, all velocity calculations were made based on data obtained from movement along that axis.

CAR_{vel}, COM_{vel} and $COM_{pelvis\text{-}vel}$ were filtered using a first order discrete Tustin lowpass filter with a filter coefficient of 0.04 seconds. Data from the robotic resistance (ROB_{vel}) was already filtered. The data from motion capture data from CAR_{vel}, COM_{vel} and $COM_{pelvis\text{-}vel}$ was then synchronized to ROB_{vel} using Matlab (Mathworks, Natick, MA, USA). In order to determine time offset between CAR_{vel} and ROB_{vel} a cross correlation was performed with the intent to sync the data at the point of highest correlation.

There is currently a lack of consensus of the definition of when the time of the CoD occurs (Sayers, 2015). Therefore, it was decided that for this study, the change of direction time was defined as when the direction of ROB_{vel} changed. Specifically, the moment the velocity changed from negative (-) to positive (+). Velocity intervals were measured at 0.1, 0.5, 1.0 and 1.5 seconds in negative (phase 1a) and positive (phase 1b) directions from the ROB_{vel} change of direction.

In order to compare between the robotic device and three dimensional motion capture, total time ($m505_{time}$), total distance ($m505_{dist}$), time phase 1a ($m505_{1a\_time}$), distance 1a ($m505_{1a\_dist}$), average velocity phase 1a ($m505_{1a\_avgvel}$), time phase 1b ($m505_{1b\_time}$), distance 1b ($m505_{1b\_dist}$) and average velocity phase 1b ($m505_{1b\_avgvel}$) outcome variables were extracted and defined from the robotic device.

2.7. Statistics

Descriptive statistical analysis was done using Excel for Mac OS 10.10.5 (Apple Inc., Cupertino, CA, USA), version 14.4.8 (Microsoft Corp., Redmond, WA, USA), specifically means and standard deviations. The remaining statistical tests were done using IBM SPSS version 21.0 (IBM, Armonk, NY, USA). The Shapiro-Wilk test was used to test for normal distribution for ROB_{vel}, CAR_{vel}, $COM_{pelvis\text{-}vel}$ and COM_{vel} data. In order to test the criterion validity the robotic resistance device, ROB_{vel} was compared to CAR_{vel}, $COM_{pelvis\text{-}vel}$ and COM_{vel} at different time points using correlation analysis. For normally distributed variables Pearson correlation (r) was used, Spearman (ρ) was used for variables that did not meet the criteria. A Bland Altman method was used to determine bias and limits of agreement of the different time points. In addition, statistical parametric mapping (SPM), specifically unpaired t-test was used to further determine if there was a difference between mean velocity for ROB_{vel} compared to CAR_{vel}, $COM_{pelvis\text{-}vel}$ and COM_{vel} data at -0.1 and +0.1 seconds from the time of change of direction.

2.8 Ethics

The participants was informed in detail about the study through a questionnaire and a waiver, which they needed to read and sign (see appendix II and III). Additionally, the subjects received the practical information prior to the day the start testing. This study was in accordance with the Helsinki-declaration and was approved by the ethical committee of Norwegian School of Sport Science. Data collection and storage was done in accordance to the standard procedure at Norwegian School of Sport Science.

The subjects in this study were expected to give their maximum effort on all the directional changes. The number of directional changes were lower than it would be in a normal training or competition setting, additionally, there were no defender/attacker to adjust to. This decreased the risk of injury significantly. Furthermore, the subjects familiarized to the protocol prior to testing initiates. There was a screening for injuries/illness, and there was staff present at all times during testing.

3.0 Results

A total of 124 trials (62 on left and 62 on right leg) were analyzed for all loaded conditions. 40 at 3kg, 40 at 6kg and 44 at 9kg. Total time, as well as phase 1a and 1b specific time ranged from 3.26 to 3.52 (total), 1.77 to 1.83 (phase 1a) and 1.47 to 1.69 (phase 1b). Average velocity for phase 1a and 1b ranged from 2.76 to 283, and 2.94 to 3.24 m/s respectively. Average velocity (m505$_{1b\_avgvel}$) throughout the trial decreased as load increased from 3kg, 6kg to 9kg (table 1). In contrast, total time (m505$_{time}$), phase 1a average velocity (m505$_{1a\_avgvel}$), phase 1a distance (m505$_{1a\_dist}$) in addition to phase 1b average velocity (m505$_{1b\_avgvel}$) and phase 1b distance (m505$_{1b\_dist}$) increased as load increased (table 1). The remaining performance variables, phase 1a total time (m505$_{1a\_time}$) and phase 1a average velocity (m505$_{1a\_avgvel}$), showed little to no change (Table 3.1). Finally, total distance, 1a distance and 1b distance all increased as load increased (table 3.1).

Table 3.1. m505 test results for the different loaded conditions

Performance variable	3 kg		6 kg		9 kg	
	M	SD	M	SD	M	SD
m505$_{time}$ (s)	3.26	.29	3.32	.35	3.52	.33
m505$_{dist}$ (m)	9.71	.33	9.81	.42	10.02	.45
m505$_{1a\_time}$ (s)	1.78	.15	1.77	.22	1.83	.15
m505$_{1a\_dist}$ (m)	4.86	.16	4.91	.21	5.01	.23
m505$_{1a\_avgvel}$ (m/s)	2.76	.17	2.83	.22	2.78	.16
m505$_{1b\_time}$ (s)	1.47	.16	1.56	.16	1.69	.21
m505$_{1b\_dist}$ (m)	4.86	.16	4.91	.21	5.01	.23
m505$_{1b\_avgvel}$ (m/s)	3.24	.27	3.10	.25	2.94	.27

m505$_{time}$, total time; m505$_{dist}$, total distance; m505$_{1a\_time}$, time phase 1a; m505$_{1a\_dist}$, distance 1a; m505$_{1a\_avgvel}$, average velocity phase 1a; m505$_{1b\_time}$, time phase 1b; m505$_{1b\_dist}$, distance 1b; m505$_{1b\_avgvel}$, average velocity phase 1b.

Strong correlations were observed comparing time intervals; 0 to -1.5, -1.0 to -1.5, 0 to -1.0, -0.5 to -1.0, 0 to -0.5, 0 to 0.5, 0.5 to 1.0, 0 to 1.0, 1.0 to 1.5 and 0 to 1.5 (Table 3.2) between ROB and CAR (average correlation=.99), ROB and COM$_{pelvis}$ (average correlation=.96) and ROB and COM (average correlation=.94) for all loaded conditions (Table 3.2). The single exception was the correlation observed between ROB and COM at the 1.0 to 1.5 time interval, specifically it displayed a weaker correlation (r=.54). The biases between ROB$_{vel}$ and CAR$_{ve,}$ are ranging from -.023 to .039 for 3kg, from -.029 to .037 for 6kg and from -.027 to .050 for 9kg. Biases between ROB$_{vel}$ and COM$_{pelvis\text{-}vel}$

range from -.149 to .128 for 3kg, from -.241 to .097 for 6kg and from -.246 to .077 for 9kg. Biases between ROB_{vel} and COM_{vel} range from -4.25 to .082 for 3kg, from -.461 to .061 for 6kg and from -4.86 to .017 for 9kg (Table 3.2). These specific time intervals have been analyzed through a Bland Altman analyses for 3, 6 and 9kg loads and are displayed below (figures 5-7).

Table 3.2. Construct validity of robotic resistance device

Load (kg)	Interval	ROB		CAR					COM_{pelvis}					COM				
		M	SD	M	SD	Bias (CI LOA)	Correlation	n/n_{tot}	M	SD	Bias (CI LOA)	Correlation	n/n_{tot}	M	SD	Bias (CI LOA)	Correlation	n/n_{tot}
3	0 to -1.5	3.00	.060	3.00	.059	-.006 (-.024;.013)	r=.99	24/40	2.94	.06	-.063 (-.10; -.024)	r=.95	23/40	2.84	.08	-.164 (-.26; -.07)	r=.79	23/40
	-1.0 to -1.5	3.39	.26	3.36	.25	-.023 (-0.55;.010)	r=1.00	24/40	3.52	.24	.128 (.006; .25)	r=.97	23/40	3.45	.23	.072 (-.073; .22)	r=.96	23/40
	0 to -1.0	2.97	.27	2.98	.27	.007 (-.02; .04)	r=1.00	40/40	2.83	.27	-.149 (-.22; -.076)	r=.99	39/40	2.72	.27	-.264 (-.38; -.14)	r=.98	39/40
	-0.5 to -1.0	4.03	.24	4.02	.23	-.012 (-.04; .02)	r=1.00	40/40	3.96	.27	-.064 (-.18; .050)	r=.98	39/40	3.94	.27	-.090 (-.22; .038)	r=.98	39/40
	0 to -0.5	1.92	.35	1.95	.36	.026 (-.023; .076)	r=1.00	40/40	1.69	.33	-.23 (-.33; .13)	r=.99	39/40	1.50	.33	-.435 (-.64; -.23)	r=.96	39/40
	0 to 0.5	-1.77	.26	-1.73	.26	.039 (.036; .11)	r=.99	40/40	-1.89	.28	-.126 (-.25; 8.43)	r=.97	39/40	-2.03	.26	-.259 (-.44; -.074)	r=.93	39/40
	0.5 to 1.0	-3.68	.38	-3.65	.38	.032 (.0027; .061)	ρ=1.00	40/40	-3.78	.39	-.094 (-.19; .005)	r=.99	39/40	-3.77	.40	-.079 (-.19; .03)	ρ=.98	39/40
	0 to 1.0	-2.73	.30	-2.69	.31	.035 (-.0069; .077)	r=1.00	40/40	-2.83	.32	-.106 (-.18; -.034)	r =1.00	39/40	-2.90	.32	-.168 (-.26; -.07)	ρ=.99	39/40
	1.0 to 1.5	-3.95	.43	-3.95	.40	-.004 (-.072; .064)	r=1.00	9/40	-3.88	.45	.042 (-.13; .22)	r=.98	8/40	-3.83	.44	.082 (-.055; .22)	r=.99	8/40
	0 to 1.5	-2.92	.16	-2.89	.16	.024 (.0091; .038)	r=1.00	9/40	-2.96	.17	-.057 (-.12; .002)	r=.98	8/40	-2.96	.17	-.067 (-.13; .0006)	r=.98	8/40
6	0 to -1.5	3.02	.07	3.00	.07	-.011 (-.02; -.001)	r=1.00	18/40	2.95	.07	-.070 (-.102; -.038)	r=.97	17/40	2.83	.09	-.182 (-.283; -.081)	r=.84	18/40
	-1.0 to -1.5	3.53	.22	3.50	.22	-.029 (-.048; -.01)	ρ=.99	18/40	3.62	.20	.097 (.002; .191)	r=.98	17/40	3.55	.18	.022 (-.139; .183)	r=.93	18/40
	0 to -1.0	2.97	.25	2.97	.25	0 (-.020; .020)	r=1.00	38/40	2.82	.24	-.154 (-.202; -.107)	r=1.00	36/40	2.71	.26	-.184 (-1.24; .872)	r=.98	39/40
	-0.5 to -1.0	4.03	.29	4.02	.28	-.016 (-.036; .005)	r=1.00	38/40	3.98	.30	-.065 (-.143; .040)	r=.99	36/40	3.96	.31	-.075 (-.207; .058)	r=.98	38/40
	0 to -0.5	1.92	.27	1.94	.29	.017 (-.019; .053)	r=1.00	39/40	1.68	.25	-.241 (-.321; -.161)	r=.99	36/40	1.46	.29	-.461 (-.627; -.295)	r=.96	39/40
	0 to 0.5	-1.65	.24	-1.62	.24	.037 (-.022; .095)	r=1.00	39/40	-1.77	.26	-.120 (-.225; -.014)	r=.98	36/40	-1.91	.26	-.252 (-.406; -.098)	r=.96	39/40
	0.5 to 1.0	-3.41	.42	-3.38	.42	.034 (.004; .064)	ρ=1.00	39/40	-3.48	.43	-.075 (-.154; .004)	ρ=.98	36/40	-3.47	.42	-.062 (-.147; .023)	ρ=.98	39/40
	0 to 1.0	-2.53	.31	-2.50	.32	.034 (.002; .066)	ρ=1.00	39/40	-2.63	.33	-.098 (-.151; -.044)	ρ=.99	36/40	-2.69	.33	-1.56 (-.239; -.074)	ρ=.98	39/40
	1.0 to 1.5	-3.88	.19	-3.87	.19	.005 (-.054; .064)	r=.99	13/40	-3.87	.25	-.005 (-.170; .159)	ρ=.48	12/40	-3.82	.22	.061 (-.156; .277)	ρ=.53	13/40
	0 to 1.5	-2.81	.11	-2.78	.11	.028 (-.016; .040	r=1.00	13/40	-2.86	.11	-.055 (-.089; -.021)	r=.99	12/40	-2.88	.10	-.067 (-.122; -.012)	r=.97	13/40
9	0 to -1.5	2.98	.14	2.97	.14	-.014 (-.033; .005)	ρ=1.00	29/44	2.90	.14	-.085 (-.131; -.040)	ρ=.97	28/44	2.77	.16	-.208 (-.311; -.106)	ρ=.89	29/44
	-1.0 to -1.5	3.75	.24	3.72	.24	-.027 (-.050; -.003)	r=1.00	29/44	3.82	.22	.077 (-.032; .186)	r=.98	28/44	3.77	.22	.015 (-.146; .177)	r=.94	29/44
	0 to -1.0	2.76	.31	2.75	.31	-.007 (-.036; .023)	ρ=1.00	44/44	2.59	.31	-.166 (-.209; -.123)	ρ=1.00	42/44	2.45	.33	-.304 (-.417; -.192)	r=.98	44/44
	-0.5 to -1.0	3.91	.32	3.90	.32	-.012 (-.033; .009)	r=1.00	44/44	3.83	.33	-.081 (-.150; -.012)	r=1.00	42/44	3.79	.38	-.118 (-.284; .047)	r=.98	44/44
	0 to -0.5	1.61	.34	1.61	.35	-.001 (-.050; .048)	r=1.00	44/44	1.36	.32	-.246 (-.341; -.150)	r=.99	42/44	1.12	.33	-.486 (-.650; -.322)	r=.97	44/44
	0 to 0.5	-1.51	.28	-1.46	.29	.050 (-.031; .131)	r=.99	44/44	-1.59	.33	-.090 (-.227; .047)	r=.98	42/44	-1.68	.34	-.170 (-.358; .019)	r=.97	44/44
	0.5 to 1.0	-3.08	.43	-3.05	.43	.022 (-.030; .075)	r=1.00	43/44	-3.15	.43	-.089 (-.183; .004)	r=.99	41/44	-3.15	.43	-.075 (-.166; .017)	r=.99	43/44
	0 to 1.0	-2.29	.34	-2.25	.34	.036 (-.005; .076)	r=1.00	43/44	-2.36	.36	-.088 (-.153; -.023)	r=1.00	41/44	-2.41	.37	-.122 (-.223; -.021)	r=.99	43.44
	1.0 to 1.5	-3.63	.22	-3.62	.21	.009 (-.033; .051)	r=1.00	22/44	-3.65	.22	-.031 (-.148; .085)	r=.89	21/44	-3.62	.23	.017 (-.146; .179)	r=.93	22/44
	0 to 1.5	-2.57	.19	-2.54	.19	.028 (.009; .048)	r=1.00	22/44	-2.60	.18	-.061 (-.087; -.034)	r=1.00	21/44	-2.62	.19	-.059 (-.101; -.017)	r=.99	22/44

Note: M= Mean; SD=Standard deviation; Bias (CI LOA) = upper and lower bound of 95% confidential interval of Mean.

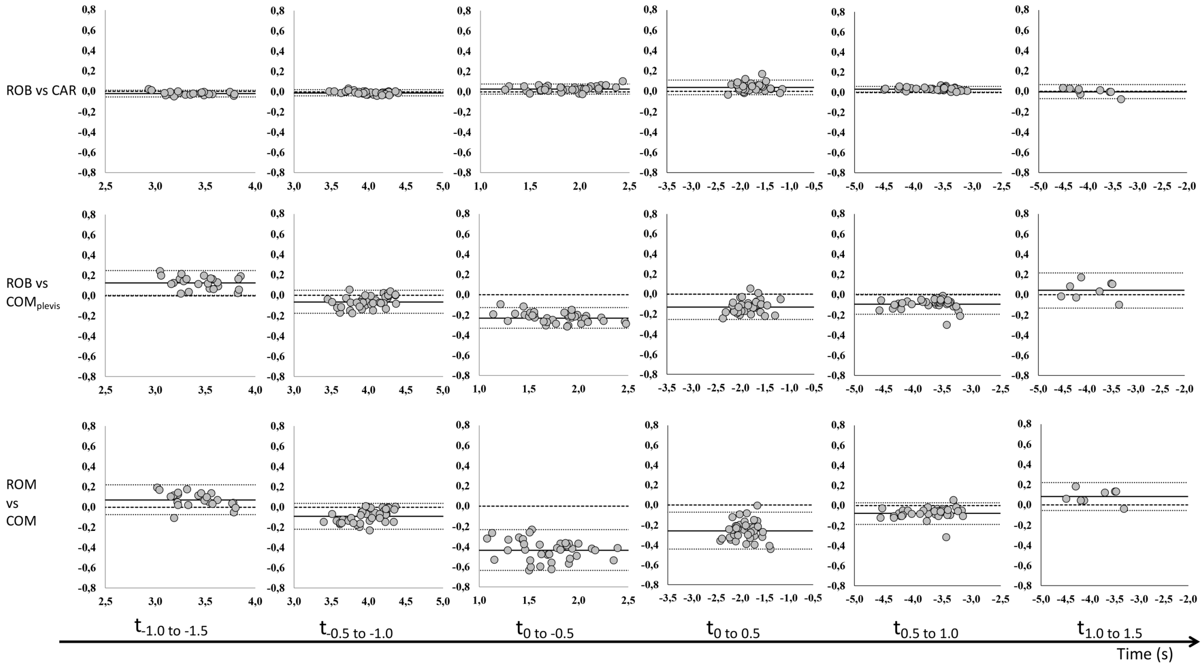


***Figure 5**. Agreement analysis of velocity data from the robotic resistance device (ROB_{vel}) and kinematic variables (CAR_{vel}, COM_{pelvic_vel} and COM_{vel}) for 0.5 second time intervals before (-) and after CoD with 3 kg load. Bland Altman plots (y axis: difference score and x-axis: mean score) with fixed bias (full line), 95% confidence interval (dotted line) and agreement (dashed line).*

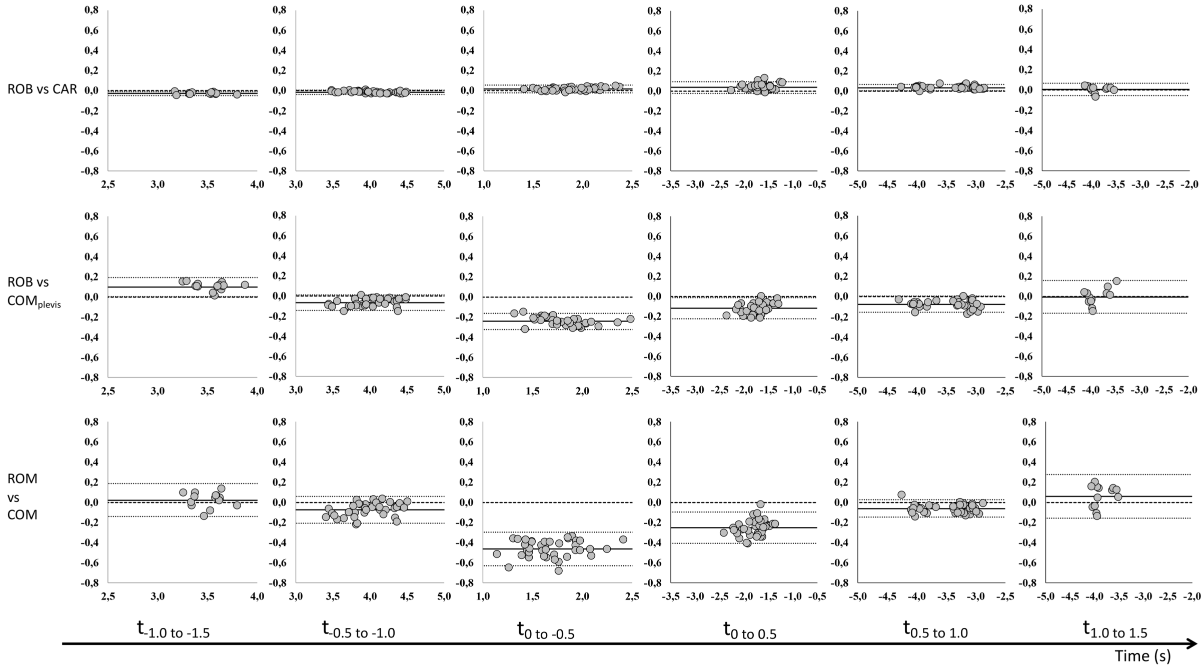


***Figure 6.** Agreement analysis of velocity data from the robotic resistance device (ROB_{vel}) and kinematic variables (CAR_{vel}, COM_{pelvic_vel} and COM_{vel}) for 0.5 second time intervals before (-) and after CoD with 6 kg load. Bland Altman plots (y axis: difference score and x-axis: mean score) with fixed bias (full line), 95% confidence interval (dotted line) and agreement (dashed line).*

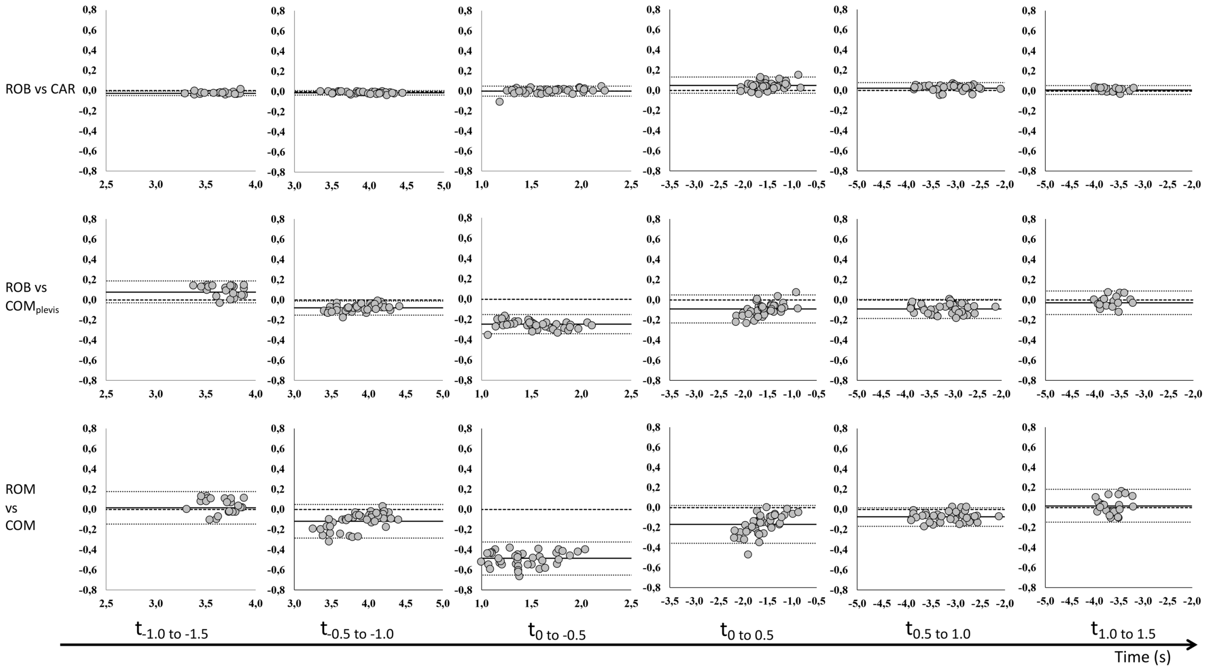


Figure 7. *Agreement analysis of velocity data from the robotic resistance device (ROB_{vel}) and kinematic variables (CAR_{vel}, COM_{pelvic_vel} and COM_{vel}) for 0.5 second time intervals before (-) and after CoD with 9 kg load. Bland Altman plots (y axis: difference score and x-axis: mean score) with fixed bias (full line), 95% confidence interval (dotted line) and agreement (dashed line).*

Comparing ROB_{vel} to CAR_{vel} through SPM analysis, there were no significant differences found for 3, 6 or 9kg loaded conditions (Figure 8). In contrast, when comparing ROB_{vel} to $COM_{pelvis\text{-}vel}$ there were significant differences found for time intervals prior to 0.5 seconds after the time of change of direction for 3, 6 and 9kg loaded conditions (Figure 9). Finally, when comparing ROB_{vel} to COM_{vel} there were no significant differences found for 3kg loaded condition (Figure 10), however, there was significant differences found for 6 and 9kg loaded conditions prior and post to the time of change of direction (Figure 10).

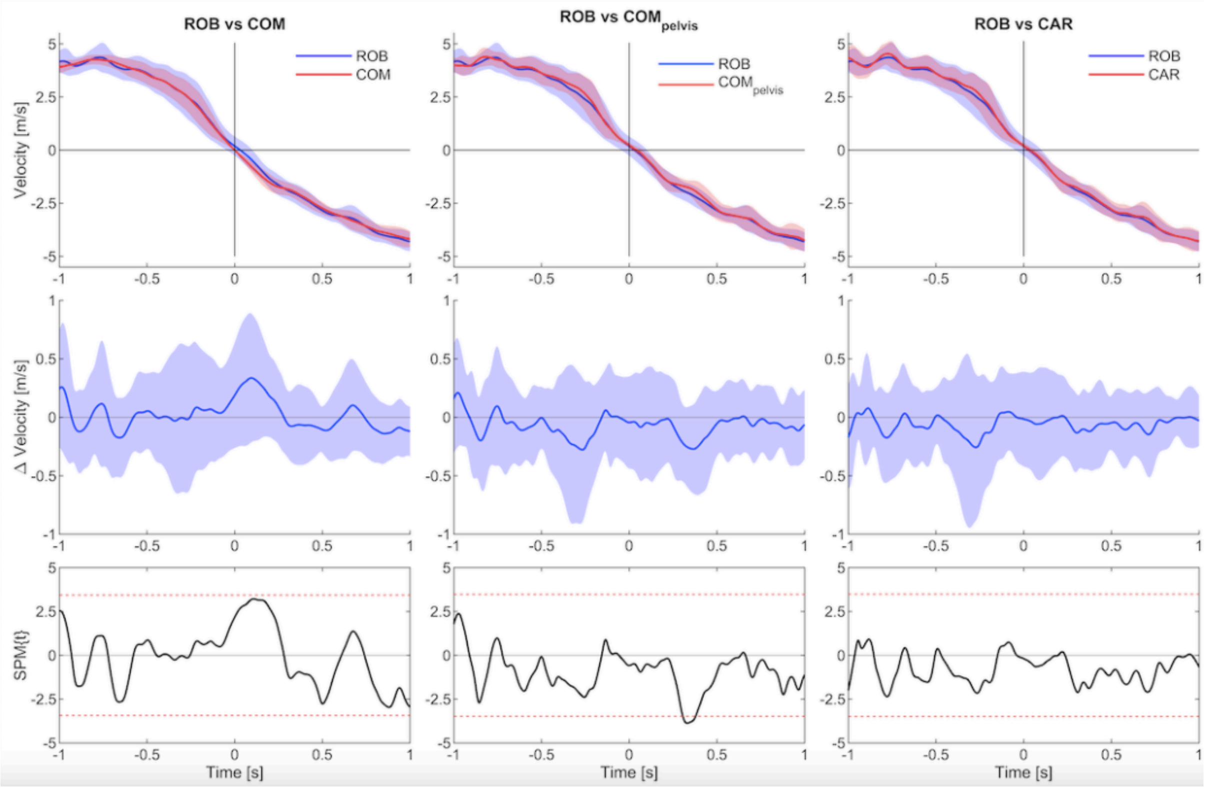


Figure 8: *SPM results with 3 kg load one second pre and post CoD (x-axis all graphs). ROB velocity is compared to COM (left column), COM$_{pelvis}$ (middle column) and CAR velocity (right column). Upper row shows average ROB velocity (blue line) with 95 % confidence interval (blue shade) and average COM, COM$_{pelvis}$ and CAR velocity (red line) with 95% confidence (red shade). Middle row shows average velocity difference (blue line) with 95% confidence interval (blue shade) for the different comparisons. Bottom row shows SPM(t) comparisons with t-value on y-axis and 95% confidence interval (red dotted line).*

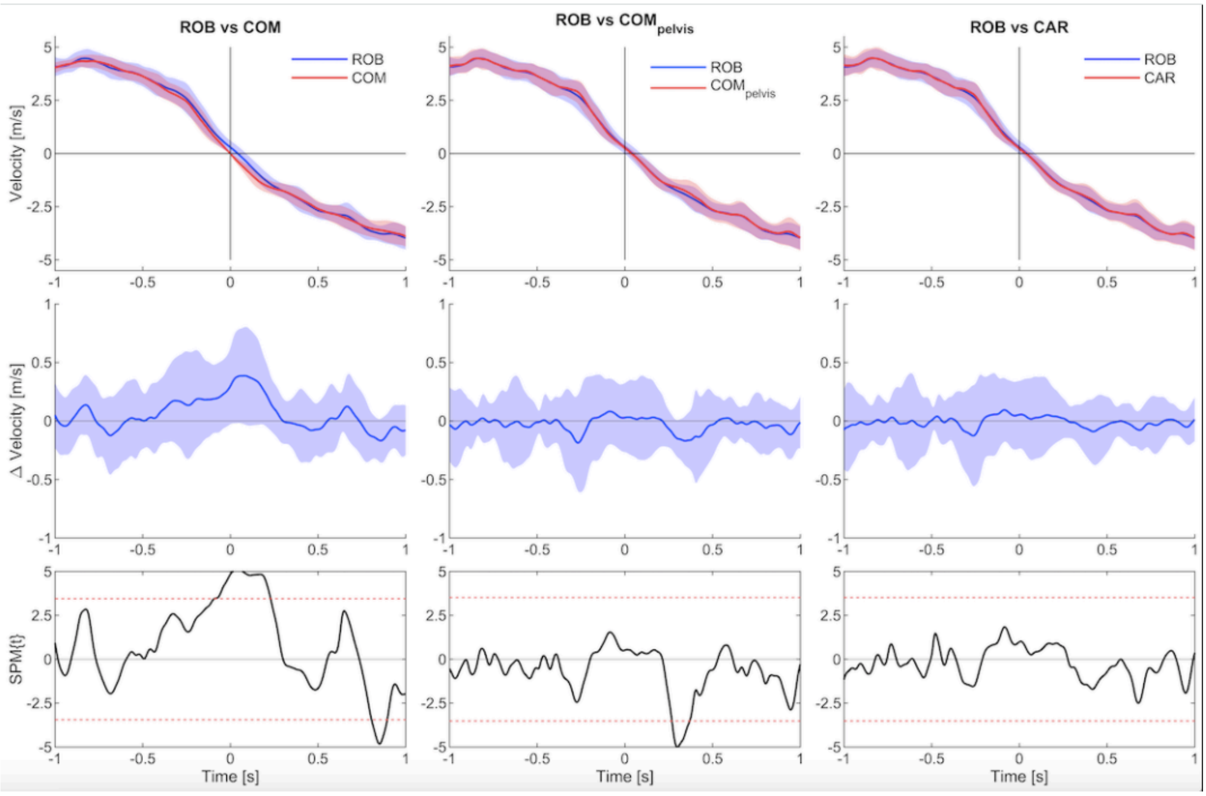


Figure 9: *SPM results with 6 kg load one second pre and post CoD (x-axis all graphs). ROB velocity is compared to COM (left column), COM*$_{pelvis}$ *(middle column) and CAR velocity (right column). Upper row shows average ROB velocity (blue line) with 95 % confidence interval (blue shade) and average COM, COM*$_{pelvis}$ *and CAR velocity (red line) with 95% confidence (red shade). Middle row shows average velocity difference (blue line) with 95% confidence interval (blue shade) for the different comparisons. Bottom row shows SPM(t) comparisons with t-value on y-axis and 95% confidence interval (red dotted line).*

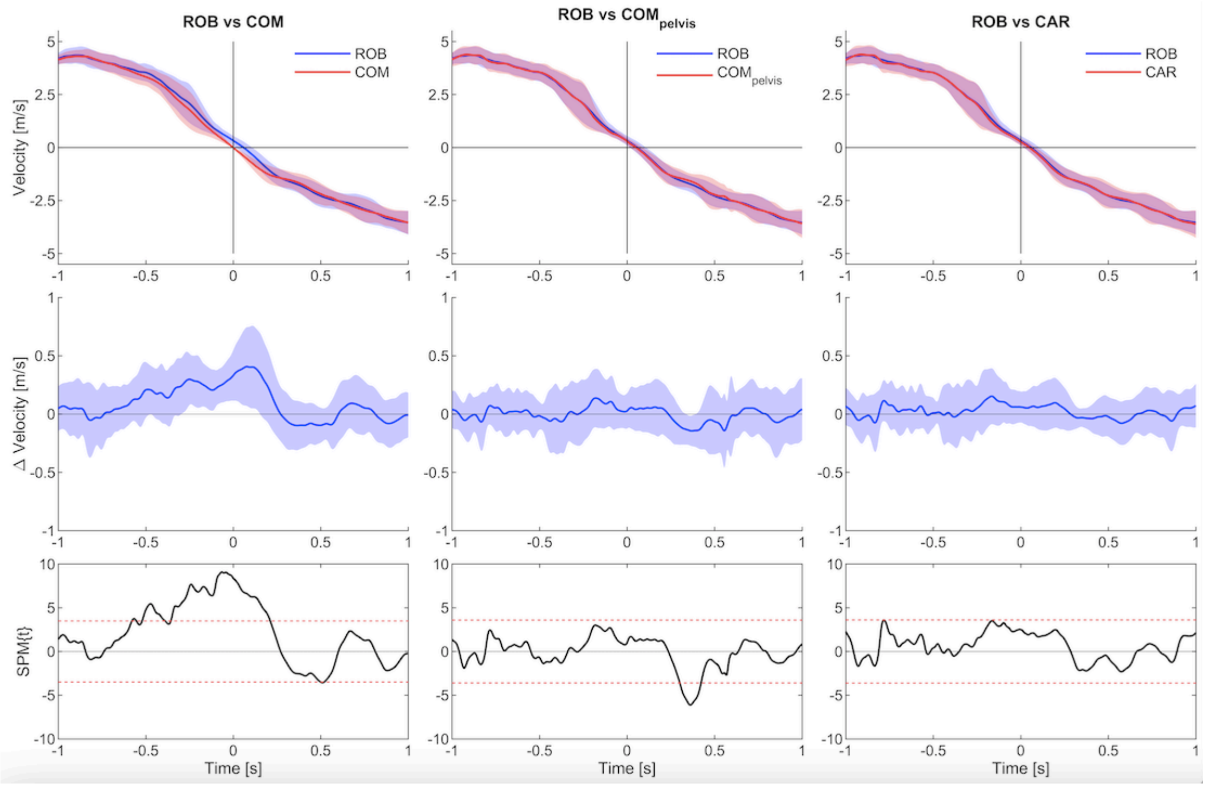


Figure 10: *SPM results with 9 kg load one second pre and post CoD (x-axis all graphs). ROB velocity is compared to COM (left column), COM*$_{pelvis}$ *(middle column) and CAR velocity (right column). Upper row shows average ROB velocity (blue line) with 95 % confidence interval (blue shade) and average COM, COM*$_{pelvis}$ *and CAR velocity (red line) with 95% confidence (red shade). Middle row shows average velocity difference (blue line) with 95% confidence interval (blue shade) for the different comparisons. Bottom row shows SPM(t) comparisons with t-value on y-axis and 95% confidence interval (red dotted line).*

4.0 Discussion

The aim of this study was to 1) develop a new protocols for the 505 test (180 degree turn) under loaded conditions (3, 6 and 9 kg) using robotic resistance and 2) determine criterion related validity of continuous velocity measurement of an athlete performing m505 test with a robotic resistance device (ROB_{vel}), and compare it to established methods used for measuring center of mass (COM_{vel} and $COM_{Pelvis-vel}$) in three-dimensional motion capture systems.

When comparing robotic resistance device to traditional motion capture measurements (COM, CAR and COM_{pelvis}) there is a very strong correlation (>.85), (Table 3.2). In addition, bland Altman plots displays little to no bias between the methods (Figures 5-7). This correlation is further supported by the SPM analysis done looking at means and spread with the three different loads, in addition to unpaired t-test (Figures 5-7). However, there is a small difference in correlation between ROB_{vel} and CAR_{vel} compared to ROB_{vel} and COM_{vel}. This could be explained by multiple factors such as; the COM is a measure of multiple markers on a moving body in high velocity, in particular arm swing which could block the cameras view of the marker. Compared to CAR, which is attached to a single spot and has little to no influence of extremity movements. In addition, when participants were decelerating at the end of phase 1a they started leaning away during the directional change. This action could impact the COM and COM_{pevlis} measurements, whereas the CAR marker was set on a single point and is not affected to the same extent by a body movements such as leaning. This action correlates with the increase in variation -0.5 to 0 second time interval prior to the directional change seen in figure 5, in addition, this specific time interval shows a lower correlation compared to the other time intervals (Table 3.2). Still, according to the tests done in this experiment, COM is a good measure for estimating center of mass in a 505 test.

Other reasons that could explain the difference can be due to the fact that the trials were synchronized in the lab after testing. The cameras were set up and calibrated to capture a good uptake of each trials, however, the resolution was not optimal for uptake <-1 and >1 seconds. This was especially true for COM, where we were unable to obtain a majority of the initial 0.5 seconds, and the last 0.5 seconds of the trials. We chose to analyse in the -1.5 to 1.5 second range due to the m505 trials usually lasting 3 seconds (Nimpius ., et al 2017), which could explain the differences seen in the result.

The course is set at 5m and for a valid result, the 505 test requires the participant to place their foot across the 5m line, not their entire body. The belt is attached at the hip, and the markers are calculating the center of mass, not the foot. Therefore, it does not mean that the participant covers the full 10m in a trial. That is why there was a difference between the distances the participants moved between the different loads (Table 3.1). One might ask how a participant can run a 505 test with a total distance registered at 9.71m (see Table 3.1). This can be explained by the use of technique, specifically the leaning action described above. Therefore, looking at the data it might not look like the participant performed a valid 505 test, when in fact they did. Additionally, the increase in total distance as the load increased can be explained by the fact that the increasing weight pulled the participant in the direction of the 1080 Sprint and further passed the 5m line. The increased weight made it more difficult to stop and change direction without increasing their total distance.

Our population in this study was a mix of gender, age, sport and performance level. This gives the test high external validity, specifically, it means that the results from this test could be used through a multitude of field based sports and across both genders. This is beneficial when establishing a new testing method, as it can be used for handball, football, tennis, basketball, floor ball players, of both genders. However, it can raise questions whether it has high enough internal validity, specifically, it means that the test might not be specific enough to for example test athletes at the highest level and distinguish between elite and novice, which was one of the initial purposes of this study.

The mean times in this study are a little slower compared to other studies testing m505, 2.6-2.8 seconds (R. Olivia,. et al 2015), (P. Jones 2009), (M. Sayers, 2015) compared to 3.26 – 5.01 seconds, (Table 3.1). The difference could be due to the fact that our participants had added weight strapped around their waist which impacted their total time and velocity, the trend of increasing weight and slower total time and velocity supports this theory (Table 3.1). In addition to only a small number are performing their sport at an elite level, compared to Sayers (2015) who tested elite rugby players.

This test was a modification of the 505-test which was introduced by Draper & Lancaster (1985), the intent is to break down CoD into one single turn to be able to build a valid method to assess and analyze it in detail. With the new method we were able to set a clear definition of phases within the test. Phase 1a which refers to the acceleration at the start and deceleration prior to turning. Phase 1b refers to the re-acceleration from the turn and finish of the test. In addition, the short distance 505-test limits the amount of linear sprinting across long distances, which could lead to the test assessing anaerobic capacity instead of CoD ability (Nimphius et al., 2017).

There have long been attempts to define CoD and find the best suitable test to assess it. Studies by Draper & Lancaster (1985), Lockie (2013) are amongst those who tried and succeeded in validation their method. However, these protocols are still time based, additionally, several new tests such as 3 cone drill are still quantified using time. This means we still have little to no knowledge about the mechanics that determine an elite CoD performance compared to a novice. With the robotic resistance deice and the increase in interest around CoD as a performance indicator and talent identification tool, there is the possibility to get more insight into the variables of CoD, such as acceleration, speed, displacement, force, power, as well as the breakdown of phases within the CoD. This idea is not new and has previously been done with GPS when investigating horizontal movement (Harper, 2020), however, the 1080 Sprint would provide more sensitivity to CoD. In addition, the robotic resistance provides the opportunity to test in the field and get the information in real time, prior to analysis and processing in a lab.

The results show that a new loaded protocol for 505 test is possible, for the three different loaded conditions. This study was done with comparative validation which investigates the difference between an already established method compared to a new one. In this case it was loaded m505 with robotic resistance compared to the normal 505 using three dimensional motion capture. According to criterion set by Nata in 2013 we were able to meet the requirements for quantitative validation including; sensitivity, measuring interval, trueness/bias, accuracy, ruggedness and measurement uncertainty. To show this we performed Pearson and Spearman correlations, unpaired t-tests and investigating biases. Our correlation analysis when comparing the methods were strong (>.85) for all loaded conditions and comparing ROB to CAR, COM_{pelvis} and COM (see table 3.2). Means, standard deviation and a paired t-test comparing the different methods showed low spread and little to no difference between the methods (figure 6, 7, 8). This in combination with the bland Altmann plots displaying little to no bias between methods (figure 5-7).

In summary, the intention was to create a new way to quantify, test and analyze CoD, which was done in my opinion. This experiment was the first of its kind to the best of my knowledge, and it was not perfect and have points were it can be improved. However, it did meet the criterion for validating a new testing method and that was the purpose of the this study. This can be the first brick laid in a new wall of how we measure CoD and I believe future studies will use what was found here to not only to be used by coaches on their athletes, but expand and be used a talent identification tool. This experiment could lead to something very exciting in our sports science world.

Practical Implications:

Using robotic resistance allows for accurate and accessible method to accurately assess players' CoD ability, and give coaches another tool to improve strength and conditioning training.

Conclusion:

The robotic resistance device provides a valid representation of athlete movement velocity during a m505 test. The observed lower correlations and greater biases for the ROB to COM comparison may be due to the moving arms and legs as the point of attachment from the device is at the pelvis.

5.0 References:

Asadi, A., Arazi, H., Young, W. B., & de Villarreal, E. S. (2016). The effects of plyometric training on change-of-direction ability: A meta-analysis. *International journal of sports physiology and performance, 11*(5), 563-573.

Barber, O. R., Thomas, C., Jones, P. A., McMahon, J. J., & Comfort, P. (2016). Reliability of the 505 Change-of-Direction Test in Netball Players. *Int J Sports Physiol Perform, 11*(3), 377-380. doi:10.1123/ijspp.2015-0215

Bloomfield, J., Polman, R., & O'Donoghue, P. (2007). Physical Demands of Different Positions in FA Premier League Soccer. *Journal of sports science & medicine, 6*(1), 63-70. Retrieved from https://pubmed.ncbi.nlm.nih.gov/24149226
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3778701/

Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding change of direction ability in sport: a review of resistance training studies. *Sports Med., 38*(12), 1045-1063. Retrieved from PM:19026020

Chaouachi, A., Manzi, V., Chaalali, A., Wong, D. P., Chamari, K., & Castagna, C. (2012). Determinants analysis of change-of-direction ability in elite soccer players. *The Journal of Strength & Conditioning Research, 26*(10), 2667-2676.

Clarke, R., Mundy, P., Aspe, R., Sargent, D., & Hughes, J. (2018). Change of Direction Technical Models: Biomechanical Principles.

Cross, M. R., Samozino, P., Brown, S. R., & Morin, J. B. (2018). A comparison between the force-velocity relationships of unloaded and sled-resisted sprinting: single vs. multiple trial methods. *European journal of applied physiology, 118*(3), 563-571. doi:10.1007/s00421-017-3796-5

DeWeese, B., & Nimphius, S. (2016). Speed and agility program design and technique. In N. T. Triplett & G. G. Haff (Eds.), *Essentials of Strength and Conditioning* (pp. 521-557). Champaign, IL, USA: Human Kinetics.

Djevalikian, R. (1993). *The relationship between asymmetrical leg power and change of running direction.* (Master). University of North Carolina, Chapel Hill, NC, USA.

Draper, JA and Lancaster, MG. The 505 test: A test for agility in the horizontal plane. Aust J Sci Med Sport 17: 15-18, 1985.

Filipčič, A., Leskošek, B., Munivrana, G., Ochiana, G., & Filipčič, T. (2017). Differences in Movement Speed Before and After a Split-Step Between Professional and Junior Tennis Players. *Journal of human kinetics, 55*, 117-125. doi:10.1515/hukin-2017-0011

Gabbett, T. J., Kelly, J. N., & Sheppard, J. M. (2008). Speed, change of direction speed, and reactive agility of rugby league players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 22*(1), 174-181. doi:10.1519/JSC.0b013e31815ef700

Hader, K., Palazzi, D., & Buchheit, M. (2015). Change of direction speed in soccer: How much braking is enough? *Kinesiology, 47*, 67-74.

Hader, K., Palazzi, D., & Buchheit, M. (2015). Change of Direction Speed in Soccer: How Much Braking Is Enough? *Kinesiology, 47*(1), 67-74. Retrieved from <Go to ISI>://WOS:000358895400009

Harper, D. J., Carling, C., & Kiely, J. (2019). High-Intensity Acceleration and Deceleration Demands in Elite Team Sports Competitive Match Play: A Systematic Review and

Meta-Analysis of Observational Studies. *Sports Med, 49*(12), 1923-1947. doi:10.1007/s40279-019-01170-1

Harper, D. J., Morin, J. B., Carling, C., & Kiely, J. (2020). Measuring maximal horizontal deceleration ability using radar technology: reliability and sensitivity of kinematic and kinetic variables. *Sports Biomech*, 1-17. doi:10.1080/14763141.2020.1792968

Helland, C., Haugen, T., Rakovic, E., Eriksrud, O., Seynnes, O., Mero, A. A., & Paulsen, G. (2019). Force-velocity profiling of sprinting athletes: single-run vs. multiple-run methods. *European journal of applied physiology, 119*(2), 465-473. doi:10.1007/s00421-018-4045-2

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *J Appl Biomech, 21*(1), 31-43. doi:10.1123/jab.21.1.31

Jones, P., Thomas, C., Dos'Santos, T., McMahon, J., & Graham-Smith, P. (2017). The Role of Eccentric Strength in 180° Turns in Female Soccer Players. *Sports, 5*, 42-53. doi:10.3390/sports5020042

Jullien, H., Bisch, C., Largouet, N., Manouvrier, C., Carling, C. J., & Amiard, V. (2008). Does a Short Period of Lower Limb Strength Training Improve Performance in Field-Based Tests of Running and Agility in Young Professional Soccer Players? *Journal of Strength and Conditioning Research, 22*(2), 404-411. doi:10.1519/JSC.0b013e31816601e5

Kobal, R., Pereira, L. A., Zanetti, V., Ramirez-Campillo, R., & Loturco, I. (2017). Effects of Unloaded vs. Loaded Plyometrics on Speed and Power Performance of Elite Young Soccer Players. *Frontiers in physiology, 8*, 742-742. doi:10.3389/fphys.2017.00742

Lockie, R. G., Dawes, J. J., & Jones, M. T. (2018). Relationships between Linear Speed and Lower-Body Power with Change-of-Direction Speed in National Collegiate Athletic Association Divisions I and II Women Soccer Athletes. *Sports (Basel), 6*(2). doi:10.3390/sports6020030

Lockie, R. G., Murphy, A. J., Knight, T. J., & Janse de Jonge, X. A. (2011). Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond Res, 25*(10), 2704-2714. doi:10.1519/JSC.0b013e31820d9f17

Lockie, R. G., Post, B. K., & Dawes, J. J. (2019). Physical Qualities Pertaining to Shorter and Longer Change-of-Direction Speed Test Performance in Men and Women. *Sports (Basel), 7*(2). doi:10.3390/sports7020045

Lockie, R. G., Schultz, A. B., Callaghan, S. J., Jeffriess, M. D., & Berry, S. P. (2013). Reliability and Validity of a New Test of Change-of-Direction Speed for Field-Based Sports: the Change-of-Direction and Acceleration Test (CODAT). *Journal of sports science & medicine, 12*(1), 88-96. Retrieved from https://pubmed.ncbi.nlm.nih.gov/24149730
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3761765/

Marcovic, G. (2007). Poor relationship between strength and power qualities and agility performance. *J Sports Med Phys Fitness, 47*(3), 276-283. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17641593

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *Journal of Strength and Conditioning Research, 16*(1), 75-82. doi:Doi 10.1519/00124278-200202000-00011

Montgomery, P. G., Pyne, D. B., & Minahan, C. L. (2010). The physical and physiological demands of basketball training and competition. *Int J Sports Physiol Perform, 5*(1), 75-86. doi:10.1123/ijspp.5.1.75

Murphy, A. J., Lockie, R. G., & Coutts, A. J. (2003). Kinematic determinants of early acceleration in field sport athletes. *Journal of sports science & medicine, 2*(4), 144-150. Retrieved from https://pubmed.ncbi.nlm.nih.gov/24688275
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3963247/

Nata. (2013). General Accreditation Guidance — Validation and verification of quantitative and qualitative test methods.

Negra, Y., Chaabene, H., Sammoud, S., Prieske, O., Moran, J., Ramirez-Campillo, R., . . . Granacher, U. (2019). The Increased Effectiveness of Loaded Versus Unloaded Plyometric Jump Training in Improving Muscle Power, Speed, Change of Direction, and Kicking-Distance Performance in Prepubertal Male Soccer Players. *Int J Sports Physiol Perform*, 1-7. doi:10.1123/ijspp.2018-0866

Negrete, R., & Brophy, J. (2000). The relationship between isokinetic open and closed chain lower extremity strength and functional performance. *Journal of sport rehabilitation, 9*(1), 46-61. doi:DOI 10.1123/jsr.9.1.46

Nimphius, S. , Geib, G., Spiteri, T. , & Carlisle, D. (2013). "Change of direction deficit" measurement in Division I American football players. Journal of Australian Strength and Conditioning, 21(Supplement 2), 115-117.

Nimphius, S., Callaghan, S. J., Bezodis, N. E., & Lockie, R. G. (2017). Change of Direction and Agility Tests: Challenging Our Current Measures of Performance *J Strength.Cond.Res., 40*(1), 1-13.

Peterson, M. D., Alvar, B. A., & Rhea, M. R. (2006). The contribution of maximal force production to explosive movement among young collegiate athletes. *Journal of Strength and Conditioning Research, 20*(4), 867-873. Retrieved from <Go to ISI>://WOS:000242414300024

Samozino, P., Rejc, E., Di Prampero, P. E., Belli, A., & Morin, J. B. (2012). Optimal force-velocity profile in ballistic movements--altius: citius or fortius? *Med Sci Sports Exerc, 44*(2), 313-322. doi:10.1249/MSS.0b013e31822d757a

Sayers, M. (2015). Influence of test distance on change of direction speed test results. Journal of Strength & Conditioning Research, 29(9).

Sheppard, J. M., & Young, W. B. (2006). Agility literature review: classifications, training and testing. *J Sports Sci, 24*(9), 919-932. doi:10.1080/02640410500457109

Sole, C. J., Mizuguchi, S., Sato, K., Moir, G. L., & Stone, M. H. (2018). Phase Characteristics of the Countermovement Jump Force-Time Curve: A Comparison of Athletes by Jumping Ability. *J Strength Cond Res, 32*(4), 1155-1165. doi:10.1519/jsc.0000000000001945

Spiteri, T., Cochrane, J. L., Hart, N. H., Haff, G. G., & Nimphius, S. (2013). Effect of strength on plant foot kinetics and kinematics during a change of direction task. *Eur J Sport Sci, 13*(6), 646-652. doi:10.1080/17461391.2013.774053

Thomas, K., French, D., & Hayes, P. R. (2009). The Effect of Two Plyometric Training Techniques on Muscular Power and Agility in Youth Soccer Players. *Journal of Strength and Conditioning Research, 23*(1), 332-335. doi:10.1519/JSC.0b013e318183a01a

Tricoli, V., Lamas, L., Carnevale, R., & Ugrinowitsch, C. (2005). Short-term effects on lower-body functional power development: Weightlifting vs. vertical jump training programs. *Journal of Strength and Conditioning Research, 19*(2), 433-437. Retrieved from <Go to ISI>://WOS:000229411100032

Wisbey, B., Montgomery, P. G., Pyne, D. B., & Rattray, B. (2010). Quantifying movement demands of AFL football using GPS tracking. *J Sci Med Sport, 13*(5), 531-536. doi:10.1016/j.jsams.2009.09.002

Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D'Lima DD, Cristofolini L, Witte H, Schmid O, Stokes I; Standardization and Terminology Committee of the International Society of Biomechanics. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine. International Society of Biomechanics. J Biomech. 2002 Apr;35(4):543-8. doi: 10.1016/s0021-9290(01)00222-6. PMID: 11934426.

Young, W. B., Hawken, M., & McDonald, L. (1996). Relationship between speed, agility and strength qualities in Australian rules football. *Strength and Conditioning Coach, 4*(4), 3-6.

Young, W. B., James, R., & Montgomery, I. (2002). Is muscle power related to running speed with changes of direction? *J Sports Med Phys Fitness, 42*(3), 282-288. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/12094116

Young, W. B., McDowell, M. H., & Scarlett, B. J. (2001). Specificity of sprint and agility training methods. *Journal of strength and conditioning research / National Strength & Conditioning Association, 15*(3), 315-319. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/11710657

Appendices

Appendix I. Warm up

Warm up

Exercise	Set/Time	Comments
Jog	2 min	
Run back/forward	2 set	Run 2 cones forward, one back. Repeat
Side shuffle	1-2 min	
Walking RDL	1-2 min	Dynamic hamstring stretch
Hip in/out	2 set	Rotate the hips while walking
Ski jumps	3 set	10 reps/leg
Sprint	5 sprints	Max effort
180 degree turn	2 on each leg	Max effort

Appendix II. All results 3kg load

Interval	1080 sprint		CAR					COM$_{pelvis}$					COM				
	M	SD	M	SD	Bias (CI LOA)	Correlation	n/n$_{tot}$	M	SD	Bias (CI LOA)	Correlation	n/n$_{tot}$	M	SD	Bias (CI LOA)	Correlation	n/n$_{tot}$
0 to -1.5	3.00	.060	3.00	.059	-.006 (-.024;.013)	r=.99	24/40	2.94	.06	-.063 (-.10; -.024)	r=.95	23/40	2.84	.08	-.164 (-.26; -.07)	r=.79	23/40
-1.0 to -1.5	3.39	.26	3.36	.25	-.023 (-0.55;.010)	r=1.00	24/40	3.52	.24	.128 (.006; .25)	r=.97	23/40	3.45	.23	.072 (-.073; .22)	r=.96	23/40
-1.4 to -1.5	2.44	.34	2.44	.30	-.002 (-.16; .16)	r=.97	24/40	2.77	.43	.335 (-.28; .95)	r=.69	23/40	2.75	.30	.326 (-.35; 1.005)	r=.40	23/40
-1.4 to -1.3	2.99	.51	2.96	.47	-.03 (-.016; .11)	r=.99	28/40	3.17	.41	.202 (-.59; .99)	r=.65	27/40	3.10	.28	.126 (-.64; .90)	r=.65	27/40
-1.2 to -1.3	3.29	.57	3.27	.52	-.03 (-.20; .14)	r=.99	36/40	3.36	.38	.054 (-.83; .94)	ρ=.50	35/40	3.34	.30	.048 (-.84; .94)	r=.63	35/40
-1.1 to -1,2	3.62	.47	3.60	.43	-.01 (-.15; .13)	r=.99	37/40	3.82	.42	.221 (-.58; 1.02)	r=.59	36/40	3.74	.29	.145 (-.61; .91)	ρ=.53	36/40
-1.0 to -1.1	4.08	.50	4.04	.44	-.05 (-.20; .11)	r=.99	39/40	4.06	.33	-.020 (-.88; .84)	r=.51	38/40	3.97	.22	-.118 (-.93; .69)	r=.58	38/40
0 to -1.0	2.97	.27	2.98	.27	.007 (-.02; .04)	r=1.00	40/40	2.83	.27	-.149 (-.22; -.076)	r=.99	39/40	2.72	.27	-.264 (-.38; -.14)	r=.98	39/40
-0.5 to -1.0	4.03	.24	4.02	0.23	-.012 (-.04; .02)	r=1.00	40/40	3.96	.27	-.064 (-.18; .050)	r=.98	39/40	3.94	.27	-.090 (-.22; .038)	r=.98	39/40
-0.9 to -1.0	4.13	.40	4.12	.34	-.009 (-.17; .15)	r=.99	40/40	4.17	.34	.035 (-.71; .78)	ρ=.39	39/40	4.14	.20	.016 (-.69; .72)	r=.45	39/40
-0.8 to -0.9	4.29	.43	4.25	.39	-.035 (-.16; .09)	r=.99	40/40	4.21	.38	-.073 (-.60; .45)	r=.79	39/40	4.19	.25	-.102 (-.60; .40)	r=.86	39/40
-0.7 to -0.8	4.17	.34	4.16	.31	-.006 (-.10; .088)	r=.99	40/40	4.11	.29	-.061 (-.54; .41)	r=.71	39/40	4.08	.27	-.085 (-.54; .37)	ρ=.76	39/40
-0.6 to -0.7	3.95	.39	3.93	.37	-.011 (-.084; .062)	r=1.00	40/40	3.83	.44	-.116 (-.46; .23)	r=.92	39/40	3.83	.39	-.11 (-.57; .35)	r=.83	39/40
-0.5 to -0.6	3.61	.45	3.61	.45	-.003 (-.073; .067)	r=1.00	40/40	3.51	.44	-.093 (-.34; .16)	r=.96	39/40	3.46	.45	-.165 (-.39; .06)	r=.97	39/40
0 to -0.5	1.92	.35	1.95	.36	.026 (-.023; .076)	r=1.00	40/40	1.69	.33	-.23 (-.33; .13)	r=.99	39/40	1.50	.33	-.435 (-.64; -.23)	r=.96	39/40
-0.4 to -0.5	3.29	.41	3.31	.40	.018 (-.040; .075)	r=1.00	40/40	3.26	.41	-.033 (-28; .21)	r=.95	39/40	3.06	.45	-.241 (-.52; .042)	r=.95	39/40
-0.3 to -0.4	2.93	.48	2.96	.47	.033 (-.05; .12)	r=1.00	40/40	2.78	.57	-.154 (.55; .25)	r=.94	39/40	2.52	.53	-.417 (-.91; .074)	r=.88	39/40
-0.2 to -0.3	2.07	.65	2.12	.66	.055 (-.060; .17)	r=1.00	40/40	1.68	.71	-.385 (-.83; .057)	ρ=.92	39/40	1.59	.61	-.496 (-.86; -.13)	r=.96	39/40
-0.1 to -0.2	1.03	.43	1.06	.45	.034 (-.047; .11)	ρ=.99	40/40	.69	.30	-.336 (-.68; .010)	ρ=.92	39/40	.59	.33	-.447 (-.80; -.098)	ρ=89	39/40
0 to -0.1	0.30	.09	0.30	.10	-.008 (-.095; .079)	ρ=.94	40/40	.04	.11	-.265 (-.55; .02)	ρ=-.38	39/40	-.25	.19	-.556 (-.96; -.15)	ρ=-.15	39/40
0 to 0.1	-.48	.16	-.47	.17	.012 (-.071; .095)	r=.97	40/40	-.78	.29	-.307 (-.601; -.01)	r=.95	39/40	-1.08	.31	-.605 (-.99; -.22)	r=.85	39/40
0.1 to 0.2	-1.37	.33	-1.34	.34	.035 (-.062; .13)	ρ=.98	40/40	-1.56	.32	-.195 (-.47; .076)	r=.91	39/40	-1.71	.27	-.337 (-.63; -.040)	r=.90	39/40
0.2 to 0.3	-1.86	.30	-1.82	.28	.041 (-0.07; .15)	ρ=.98	40/40	-1.83	.27	.022 (-.36; .401)	r=.77	39/40	-2.03	.25	-.161 (-.60; .28)	ρ=.76	39/40
0.3 to 0.4	-2.33	.37	-2.27	.36	.06 (-.032; .15)	ρ=.99	40/40	-2.39	.56	-.057 (-.59; .47)	r=.91	39/40	-2.47	.36	-.136 (-.47; .202)	ρ=.88	39/40
0.4 to 0.5	-2.80	.38	-2.75	.38	.051 (-.015; .12)	r=1.00	40/40	-2.86	.40	-.069 (-.51; .37)	r=.84	39/40	-2.85	.28	-.056 (-.44; .32)	r=.87	39/40
0 to 0.5	-1.77	.26	-1.73	.26	.039 (.036; .11)	r=.99	40/40	-1.89	.28	-.126 (-.25; 8.43)	r=.97	39/40	-2.03	.26	-.259 (-.44; -.074)	r=.93	39/40
0.5 to 0.6	-2.99	.30	-2.95	.29	.042 (-.056; .14)	r=.99	40/40	-3.12	.36	-.130 (-.52; .26)	r=.83	39/40	-3.21	.33	-.210 (-.76; .34)	ρ=.50	39/40
0.6 to 0.7	-3.37	.54	-3.32	.51	.054 (-.045; .15)	ρ=.99	40/40	-3.55	.54	-.157 (-.56; .25)	r=.93	38/40	-3.54	.43	-.157 (-.63; .32)	ρ=.88	39/40
0.7 to 0.8	-3.75	.55	-3.71	.54	.039 (-.037; .12)	ρ=.99	40/40	-3.78	.48	-.034 (-.52; .46)	r=.89	39/40	-3.78	.41	-.030 (-.57; .51)	ρ=.87	39/40
0.8 to 0.9	-4.03	.40	-4.02	.41	.014 (-.058; .087)	ρ=.99	40/40	-4.12	.51	-.089 (-.57; .39)	r=.88	39/40	-4.07	.44	-.028 (-.35; .30)	ρ=.88	39/40
0.9 to 1.0	-4.28	.45	-4.27	.44	.006 (-.064; .076)	ρ=.99	40/40	-4.35	.50	-.063 (-.38; .25)	r=.95	39/40	-4.26	.45	.025 (-.32; .38)	ρ=.89	39/40
0.5 to 1.0	-3.68	.38	-3.65	.38	.032 (.0027; .061)	ρ=1.00	40/40	-3.78	.39	-.094 (-.19; .005)	r=.99	39/40	-3.77	.40	-.079 (-.19; .03)	ρ=.98	39/40
0 to 1.0	-2.73	.30	-2.69	.31	.035 (-.0069; .077)	r=1.00	40/40	-2.83	.32	-.106 (-.18; -.034)	r =1.00	39/40	-2.90	.32	-.168 (-.26; -.07)	ρ=.99	39/40
1.0 to 1.1	-4.32	.50	-4.32	.48	.002 (-.069; .073)	r=1.00	38/40	-4.34	.56	-.060 (-.46; .33)	r=.94	36/40	-4.33	.48	-.031 (-.37; .305)	r=.94	36/40
1.1 to 1.2	-4.36	.52	-4.35	.52	.011 (-.061; .082)	r=1.00	30/40	-4.50	.49	-.153 (-.604; .30)	r=.89	29/40	-4.34	.47	.009 (-.48; .49)	r=.87	29/40
1.2 to 1.3	-4.36	.44	-4.33	.40	.030 (-.049; .11)	ρ=.99	22/40	-4.34	.42	.038 (-.36; .44)	r=.89	22/40	-4.20	.37	.153 (-.25; .55)	ρ=.91	22/40

1.3 to 1.4	-4.18	.54	-4.18	.52	.001 (-.075; .076)	r=1.00	16/40	-4.12	.48	.066 (-.53; .66)	r=.83	16/40	-4.04	.47	.110 (-.19; .41)	r=.97	15/40
1.4 to 1.5	-3.66	.76	-3.69	.70	-.031 (-.17; .11)	r=1.00	9/40	-3.27	.68	.338 (-.26; .93)	r=.93	8/40	-3.57	.60	.127 (-.46; .71)	r=.95	8/40
1.0 to 1.5	-3.95	.43	-3.95	.40	-.004 (-.072; .064)	r=1.00	9/40	-3.88	.45	.042 (-.13; .22)	r=.98	8/40	-3.83	.44	.082 (-.055; .22)	r=.99	8/40
0 to 1.5	-2.92	.16	-2.89	.16	.024 (.0091; .038)	r=1.00	9/40	-2.96	.17	-.057 (-.12; .002)	r=.99	8/40	-2.96	.17	-.067 (-.13; .0006)	r=.98	8/40

Apenix III. All results 6kg load

Interval	1080 sprint		CAR					COM_{pelvis}					COM				
	M	SD	M	SD	Bias (CI LOA)	Correlation	n/n_{tot}	M	SD	Bias (CI LOA)	Correlation	n/n_{tot}	M	SD	Bias (CI LOA)	Correlation	n/n_{tot}
0 to -1.5	3.02	.07	3.00	.07	-.011 (-.02; -.001)	r=1.00	18/40	2.95	.07	-.070 (-.102; -.038)	r=.97	17/40	2.83	.09	-.182 (-.283; -.081)	r=.84	18/40
-1.0 to -1.5	3.53	.22	3.50	.22	-.029 (-.048; -.01)	ρ=.99	18/40	3.62	.20	.097 (.002; .191)	r=.98	17/40	3.55	.18	.022 (-.139; .183)	r=.93	18/40
-1.4 to -1.5	2.62	.40	2.61	.37	-.019 (-.105; .07)	ρ=.98	18/40	2.89	.38	.260 (-.118; .639)	ρ=.78	17/40	2.87	.24	.243 (-.332; .818)	ρ=.65	18/40
-1.4 to -1.3	3.06	.49	3.03	.46	-.028 (-.13; .07)	r=1.00	29/40	3.16	.42	.104 (-.306; .513)	r=.90	27/40	3.12	.28	.057 (-.489; .602)	r=.88	29/40
-1.2 to -1.3	3.30	.40	3.27	.40	-.036 (-.17; .101)	r=.98	35/40	3.45	.38	.148 (-.263; .559)	r=.86	33/40	3.46	.28	.156 (-.273; .585)	r=.85	35/40
-1.1 to -1,2	3.87	.38	3.83	.36	-.045 (-.14; .05)	r=.99	36/40	3.99	.40	.123 (-.230; .476)	r=.90	34/40	3.84	.26	-.035 (-.468; .399)	r=.83	36/40
-1.0 to -1.1	4.08	.36	4.06	.34	-.022 (-.098; .05)	r=1.00	38/40	4.12	.34	.044 (-.367; .455)	r=.82	36/40	4.07	.22	-.005 (-.463; .453)	r=.78	38/40
0 to -1.0	2.97	.25	2.97	.25	0 (-.020; .020)	r=1.00	38/40	2.82	.24	-.154 (-.202; -.107)	r=1.00	36/40	2.71	.26	-.184 (-1.24; .872)	r=.98	39/40
-0.5 to -1.0	4.03	.29	4.02	.28	-.016 (-.036; .005)	r=1.00	38/40	3.98	.30	-.065 (-.143; .040)	r=.99	36/40	3.96	.31	-.075 (-.207; .058)	r=.98	38/40
-0.9 to -1.0	4.28	.43	4.24	.41	-.032 (-.010; .033)	r=1.00	38/40	4.33	.47	.043 (-.314; .400)	r=.92	36/40	4.25	.31	-.024 (-.375; .327)	r=.93	38/40
-0.8 to -0.9	4.32	.41	4.30	.40	-.023 (-.070; .024)	r=1.00	39/40	4.26	.41	-.065 (-.432; .302)	r=.90	36/40	4.24	.32	-.076 (-.436; .285)	r=.91	39/40
-0.7 to -0.8	4.13	.31	4.12	.30	-.010 (-.05; .03)	r=1.00	39/40	4.04	.30	-.088 (-.461; .285)	r=.80	36/40	4.09	.33	-.042 (-.442; .358)	r=.80	39/40
-0.6 to -0.7	3.87	.36	3.86	.34	-.013 (-.056; .030)	r=1.00	39/40	3.77	.46	-.104 (-.459; .251)	ρ=.92	36/40	3.80	.40	-.069 (-.425; .287)	r=.89	39/40
-0.5 to -0.6	3.60	.44	3.60	.44	-.003 (-.05; .04)	ρ=1.00	39/40	3.49	.46	-.104 (-.383; .174)	ρ=.93	36/40	3.46	.42	-.146 (-.412; .119)	ρ=.94	39/40
0 to -0.5	1.92	.27	1.94	.29	.017 (-.019; .053)	r=1.00	39/40	1.68	.25	-.241 (-.321; -.161)	r=.99	36/40	1.46	.29	-.461 (-.627; -.295)	r=.96	39/40
-0.4 to -0.5	3.25	.39	3.27	.40	.016 (-.034; .065)	r=1.00	39/40	3.16	.35	-.089 (-.364; .186)	r=.93	36/40	2.98	.38	-.273 (-.593; .047)	r=.91	39/40
-0.3 to -0.4	2.90	.36	2.93	.37	.029 (-.038; .097)	r=1.00	39/40	2.76	.43	-.128 (-.414; .158)	r=.94	36/40	2.49	.42	-.408 (-.821; .006)	r=.87	39/40
-0.2 to -0.3	2.06	.43	2.10	.45	.035 (-.028; .097)	r=1.00	39/40	1.69	.55	-.352 (-.780; .076)	r=.93	36/40	1.55	.52	-.512 (-.899; -.125	r=.93	39/40
-0.1 to -0.2	1.09	.40	1.10	.43	.016 (-.065; .097)	ρ=.99	39/40	.74	.35	-.345 (-.562; .-128)	ρ=.95	36/40	.57	.36	-.514 (-.793; -.236)	ρ=.91	39/40
0 to -0.1	.32	.11	0.32	.13	-.011 (-.087; .064)	ρ=.95	39/40	.03	.04	-.287 (-.507; -.067)	ρ=.12	36/40	-.27	.18	-.590 (-.963; -.218)	ρ=.11	39/40
0 to 0.1	-.46	.14	-.46	.14	-.001 (-.070; .068)	r=.97	39/40	-.77	.25	-.312 (-.532; -.091)	r=.98	36/40	-1.09	.26	-.629 (-.968; -.291)	r=.80	39/40
0.1 to 0.2	-1.27	.25	-1.25	.25	.025 (-.055; .104)	r=.99	39/40	-1.44	.23	-.174 (-.414; .067)	r=.88	36/40	-1.62	.23	-.351 (-.658; -.044)	r=.79	39/40
0.2 to 0.3	-1.76	.27	-1.71	.27	.050 (-.030; .130)	r=.99	39/40	-1.74	.38	.025 (-.337; .386)	ρ=.86	36/40	-1.89	.30	-.125 (-.438; .189)	r=.85	39/40
0.3 to 0.4	-2.17	.44	-2.11	.44	.056 (-.015; .128)	ρ=.99	39/40	-2.23	.55	-.068 (-.489; .353)	ρ=.91	36/40	-2.29	.38	-.122 (-.462; .217)	ρ=.87	39/40
0.4 to 0.5	-2.62	.36	-2.56	.37	.054 (-.011; .119	r=1.00	39/40	-2.68	.42	-.078 (-.490; .334)	r=.87	36/40	-2.65	.32	-.033 (-.433; .366)	r=.83	39/40
0 to 0.5	-1.65	.24	-1.62	.24	.037 (-.022; .095)	r=1.00	39/40	-1.77	.26	-.120 (-.225; -.014)	r=.98	36/40	-1.91	.26	-.252 (-.406; -.098)	r=.96	39/40
0.5 to 0.6	-2.77	.39	-2.72	.38	.052 (-.014; .118)	r=1.00	39/40	-2.83	.47	-.039 (-.426; .348)	r=.91	36/40	-2.92	.41	-.148 (-.636; .341)	ρ=.84	39/40
0.6 to 0.7	-3.12	.52	-3.06	.52	.056 (-.012; .123)	ρ=.99	39/40	-3.28	.52	-1.63 (-.530; .204)	ρ=.94	36/40	-3.28	.43	-.166 (-.623; .291)	ρ=.82	39/40
0.7 to 0.8	-3.55	.48	-3.50	.48	.042 (-.021; .104)	r=1.00	39/40	-3.56	.45	-.031 (-.404; .341)	r=.92	36/40	-3.50	.43	.049 (-.368; .465)	ρ=.89	39/40
0.8 to 0.9	-3.68	.49	-3.67	.49	.016 (-.062; .094)	r=1.00	39/40	-3.71	.57	-.023 (-.458; .411)	r=.92	36/40	-3.71	.49	-.026 (-.415; .364)	ρ=.86	39/40
0.9 to 1.0	-3.94	.50	-3.94	.49	.001 (-.082; .085)	ρ=.98	39/40	-4.04	.50	-.119 (-.472; .234)	ρ=.86	36/40	-3.96	.43	-.0.19 (-.349; .310)	ρ=.86	39/40
0.5 to 1.0	-3.41	.42	-3.38	.42	.034 (.004; .064)	ρ=1.00	39/40	-3.48	.43	-.075 (-.154; .004)	ρ=.98	36/40	-3.47	.42	-.062 (-.147; .023)	ρ=.98	39/40

0 to 1.0	-2.53	.31	-2.50	.32	.034 (.002; .066)	ρ=1.00	39/40	-2.63	.33	-.098 (-.151; -.044)	ρ=.99	36/40	-2.69	.33	-1.56 (-.239; -.074)	ρ=.98	39/40
1.0 to 1.1	-4.07	.45	-4.06	.43	.011 (-.072; .093)	r=1.00	35/40	-4.12	.57	-.047; (-.449; .355)	r=.95	33/40	-4.04	.47	.030 (-.259; .318)	ρ=.91	35/40
1.1 to 1.2	-3.87	.39	-3.87	.37	.006 (-.061; .073)	r=1.00	28/40	-3.97	.42	-.043 (-.532; .445)	r=.84	27/40	-3.96	.32	-.084 (-.563; .395)	r=.78	28/40
1.2 to 1.3	-4.03	.36	-4.01	.35	.019 (-.031; .070)	r=1.00	25/40	-3.99	.37	-.010 (-.331; .331)	r=.86	20/40	-3.98	.30	.051 (-.340; .443)	r=.83	25/40
1.3 to 1.4	-4.07	.27	-4.06	.26	.015 (-.060; .089)	r=.99	19/40	-4.06	.26	.001 (-.288; .289)	ρ=.86	18/40	-3.93	.24	.138 (-.178; .454)	r=.81	19/40
1.4 to 1.5	-4.06	.37	-4.05	.37	.006 (-.076; .088)	r=.99	13/40	-3.95	.65	.111 (-.564; .787)	r=.90	12/40	-3.86	.46	.197 (-.264; .658)	r=.86	13/40
1.0 to 1.5	-3.88	.19	-3.87	.19	.005 (-.054; .064)	r=.99	13/40	-3.87	.25	-.005 (-.170; .159)	ρ=.89	12/40	-3.82	.22	.061 (-.156; .277)	ρ=.53	13/40
0 to 1.5	-2.81	.11	-2.78	.11	.028 (-.016; .040	r=1.00	13/40	-2.86	.11	-.055 (-.089; -.021)	r=.99	12/40	-2.88	.10	-.067 (-.122; -.012)	r=.97	13/40

Appendix IV. All results 9kg load

Interval	1080 sprint		CAR					COM_{pelvis}					COM				
	M	SD	M	SD	Bias (CI LOA)	Correlation	n/n_{tot}	M	SD	Bias (CI LOA)	Correlation	n/n_{tot}	M	SD	Bias (CI LOA)	Correlation	n/n_{tot}
0 to -1.5	2.98	.14	2.97	.14	-.014 (-.033; .005)	ρ=1.00	29/44	2.90	.14	-.085 (-.131; -.040)	ρ=.97	28/44	2.77	.16	-.208 (-.311; -.106)	ρ=.89	29/44
-1.0 to -1.5	3.75	.24	3.72	.24	-.027 (-.050; -.003)	r=1.00	29/44	3.82	.22	.077 (-.032; .186)	r=.98	28/44	3.77	.22	.015 (-.146; .177)	r=.94	29/44
-1.4 to -1.5	3.10	.48	3.08	.47	-.024 (-.111; .062)	r=1.00	29/44	3.20	.46	.104 (-.284; .491)	r=.92	28/44	3.14	.37	.040 (-.400; .481)	r=.89	29/44
-1.4 to -1.3	3.27	.55	3.26	.54	-.016 (-.081; .049)	r=1.00	37/44	3.42	.55	.153 (-.195; .501)	r=.95	36/44	3.40	.41	.125 (-.343; .593)	r=.92	37/44
-1.2 to -1.3	3.74	.44	3.71	.43	-.037 (-.110; .037)	r=1.00	40/44	3.89	.40	.121 (-.257; .499)	r=.90	39/40	3.81	.29	.037 (-.365; .438)	r=.93	40/44
-1.1 to -1,2	4.03	.30	4.01	.29	-.021 (-.076; .034)	r=1.00	40/44	4.06	.32	.042 (-.304; .388)	r=.84	39/44	4.03	.25	-.001 (-.314; .311)	r=.85	40/44
-1.0 to -1.1	4.23	.29	4.20	.28	-.030 (-.083; .023)	ρ=.99	43/44	4.32	.30	.083 (-.222; .388)	ρ=.81	41/44	4.23	.25	.002 (-.329; .333)	ρ=.81	43/44
0 to -1.0	2.76	.31	2.75	.31	-.007 (-.036; .023)	ρ=1.00	44/44	2.59	.31	-.166 (-.209; -.123)	ρ=1.00	42/44	2.45	.33	-.304 (-.417; -.192)	ρ=.98	44/44
-0.5 to -1.0	3.91	.32	3.90	.32	-.012 (-.033; .009)	r=1.00	44/44	3.83	.33	-.081 (-.150; -.012)	r=1.00	42/44	3.79	.38	-.118 (-.284; .047)	r=.98	44/44
-0.9 to -1.0	4.34	.38	4.31	.37	-.026 (-.064; .012)	r=1.00	44/44	4.27	.43	-.079 (-.373; .214)	r=.94	42/44	4.29	.33	-.052 (-.311; .207)	r=.94	44/44
-0.8 to -0.9	4.08	.35	4.07	.35	-.011 (-.041; .019)	ρ=1.00	44/44	4.01	.36	-.073 (-.431; .284)	ρ=.74	42/44	4.09	.37	.004 (-.261; .269)	ρ=.89	44/44
-0.7 to -0.8	3.96	.35	3.94	.35	-.015 (-.052; .022)	ρ=1.00	44/44	3.93	.37	-.040 (-.373; .294)	r=.89	42/44	3.87	.42	-.087 (-.495; .320)	r=.87	44/44
-0.6 to -0.7	3.73	.39	3.72	.39	-.012 (-.059; .035)	r=1.00	44/44	3.62	.45	-.119 (-.398; .159)	ρ=.95	42/44	3.56	.44	-.171 (-.419; .077)	r=.96	44/44
-0.5 to -0.6	3.42	.45	3.43	.44	.005 (-.041; .049)	ρ=.99	44/44	3.34	.50	-.092 (-.397; .214)	ρ=.92	42/44	3.15	.47	-.275 (-.618; .067)	ρ=.89	44/44
0 to -0.5	1.61	.34	1.61	.35	-.001 (-.050; .048)	r=1.00	44/44	1.36	.32	-.246 (-.341; -.150)	r=.99	42/44	1.12	.33	-.486 (-.650; -.322)	r=.97	44/44
-0.4 to -0.5	3.07	.52	3.08	.53	.013 (-.056; .082)	ρ=.99	44/44	2.93	.64	-.137 (-.561; .287)	ρ=.89	42/44	2.68	.60	-.389 (-.843; .065)	ρ=.87	44/44
-0.3 to -0.4	2.41	.63	2.42	.66	.014 (-.090; .118)	r=1.00	44/44	2.10	.76	-.295 (-.767; .177)	r=.95	42/44	1.88	.68	-.529 (-.978; -.079)	r=.94	44/44
-0.2 to -0.3	1.50	.51	1.50	.54	.001 (-.100; .101)	ρ=1.00	44/44	1.14	.43	-.360 (-.717; -.004)	ρ=.92	42/44	1.00	.44	-.498 (-.781; -.214)	ρ=.95	44/44
-0.1 to -0.2	.79	.21	.78	.22	-.010 (-.072; .052)	r=.99	44/44	.59	.15	-.211 (-.483; .061)	r=.77	42/44	.34	.20	-.450 (-.729; -.171)	r=.77	44/44
0 to -0.1	.27	.07	.25	.06	-.021 (-.094; .052)	r=.86	44/44	.04	.06	-.230 (-.430; -.031)	r=-.13	42/44	-.30	.18	-.568 (-.979; -.157)	r=-.31	44/44
0 to 0.1	-.41	.13	-.41	.14	.005 (-.085; .094)	r=.95	44/44	-.69	.24	-.274 (-.527; -.021)	r=.93	42/44	-.96	.29	-.546 (-.953; -.138)	r=.79	44/44
0.1 to 0.2	-1.20	.31	-1.16	.32	.039 (-.074; .152)	r=.98	44/44	-1.36	.35	-.170 (-.489; .149)	r=.89	42/44	-1.44	.34	-.240 (-.589; .109)	r=.86	44/44
0.2 to 0.3	-1.68	.31	-1.61	.31	.070 (-.038; .178)	ρ=.97	44/44	-1.63	.35	.034 (-.310; .379)	ρ=.81	42/44	-1.67	.35	.010 (-.361; .381)	ρ=.81	44/44
0.3 to 0.4	-1.97	.41	-1.89	.42	.072 (-.032; .175)	r=.99	44/44	-1.96	.56	.005 (-.455; .464)	r=.93	42/44	-1.99	.47	-.024 (-.417; .366)	r=.91	44/44
0.4 to 0.5	-2.30	.49	-2.23	.49	.066 (-.016; .147)	r=1.00	44/44	-2.33	.54	-.044 (-.447; .358)	r=.93	42/44	-2.35	.41	-.053 (-.393; .287)	r=.94	44/44
0 to 0.5	-1.51	.28	-1.46	.29	.050 (-.031; .131)	r=.99	44/44	-1.59	.33	-.090 (-.227; .047)	r=.98	42/44	-1.68	.34	-.170 (-.358; .019)	r=.97	44/44
0.5 to 0.6	-2.58	.35	-2.53	.35	.045 (-.035; .124)	r=.99	44/44	-2.67	.42	-.098 (-.528; .332)	r=.85	42/44	-2.68	.39	-.105 (-.559; .350)	r=.81	44/44
0.6 to 0.7	-2.83	.53	-2.79	.52	.038 (-.043; .120)	r=1.00	44/44	-2.92	.58	-.096 (-.479; .287)	r=.94	42/44	-2.96	.52	-.126 (-.615; .364)	r=.89	44/44
0.7 to 0.8	-3.09	.56	-3.05	.55	.033 (-.054; .120)	r=1.00	44/44	-3.14	.53	-.066 (-.522; .390)	r=.91	42/44	-3.17	.46	-.083 (-.529; .363)	r=.92	44/44
0.8 to 0.9	-3.36	.49	-3.36	.50	-.001 (-.110; .108)	r=.99	44/44	-3.46	.55	-.108 (-.581; .365)	r=.90	42/44	-3.42	.48	-.052 (-.513; .408)	ρ=.89	44/44

0.9 to 1.0	-3.58	.51	-3.59	.51	-.006 (-.098; .085)	r=1.00	43/44	-3.65	.56	-.077 (-.482; .328)	r=.93	41/44	-3.59	.46	-.008 (-.377; .361)	r=.93	43/44
0.5 to 1.0	-3.08	.43	-3.05	.43	.022 (-.030; .075)	r=1.00	43/44	-3.15	.43	-.089 (-.183; .004)	r=.99	41/44	-3.15	.43	-.075 (-.166; .017)	r=.99	43/44
0 to 1.0	-2.29	.34	-2.25	.34	.036 (-.005; .076)	r=1.00	43/44	-2.36	.36	-.088 (-.153; -.023)	r=1.00	41/44	-2.41	.37	-.122 (-.223; -.021)	r=.99	43.44
1.0 to 1.1	-3.72	.43	-3.72	.43	-.002 (-.084; .079)	r=1.00	42/44	-3.80	.47	-.090 (-.500; .321)	r=.90	40/44	-3.75	.44	-.026 (-.450; .398)	r=.88	42/44
1.1 to 1.2	-3.79	.57	-3.78	.56	.005 (-.058; .067)	ρ=.99	36/44	-3.82	.64	-.035 (-.370; .300)	ρ=.91	35/44	-3.80	.51	-.016 (-.405; .373)	ρ=.88	36/44
1.2 to 1.3	-3.76	.48	-3.75	.45	.017 (-.056; .090)	r=1.00	31/44	-3.85	.45	-.080 (-.459; .300)	r=.92	30/44	-3.81	.38	-.045 (-.394; .304)	r=.94	31/44
1.3 to 1.4	-3.91	.27	-3.88	.26	.025 (-.032; .083)	r=.99	27/44	-3.90	.29	-.010 (-.463; .443)	r=.66	26/44	-3.83	.24	.082 (-.233; .398)	r=.81	27/44
1.4 to 1.5	-3.86	.28	-3.84	.26	.017 (-.041; .075)	r=1.00	22/44	-3.78	.31	.053 (-.372; .477)	r=.73	21/44	-3.75	.29	.107 (-.314; .527)	r=.72	22/44
1.0 to 1.5	-3.63	.22	-3.62	.21	.009 (-.033; .051)	r=1.00	22/44	-3.65	.22	-.031 (-.148; .085)	r=.96	21/44	-3.62	.23	.017 (-.146; .179)	r=.93	22/44
0 to 1.5	-2.57	.19	-2.54	.19	.028 (.009; .048)	r=1.00	22/44	-2.60	.18	-.061 (-.087; -.034)	r=1.00	21/44	-2.62	.19	-.059 (-.101; -.017)	r=.99	22/44

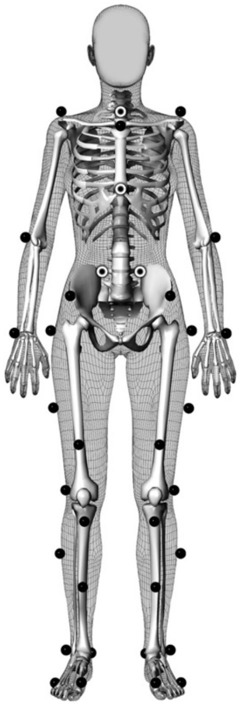
Appendix V. Marker set up

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 (10 markers) (see figure for tracking markers):

- Right tuberositas tibia (R_TUB) (tracking)
- Left tuberositas tibia (L_TUB) (tracking)
- Midpoint R_TUB and R lateral malleol projected onto tibia (R_LEG_ANT) (tracking)
- Midpoint L_TUB and L lateral malleol projected onto tibia (L_LEG_ANT) (tracking)
- Midpoint R_TUB and R_LEG_ANT lateral on leg (fibula) (R_LEG_LAT) (tracking)
- Midpoint L_TUB and L_LEG_ANT lateral on leg (fibula) (L_LEG_LAT) (tracking)
- Right lateral malleolus (RFAL)
- Left lateral malleolus (LFAL)
- Right medial malleolus (RTAM)
- Left medial malleolus (LTAM)



Thigh (10 markers) (see figure for tracking markers):

- Right greater trochanter (RFT)
- Left greater trochanter (LFT)

- Midpoint RIAS and right lateral condyle knee lateral on thigh (R_THIGH_LAT) (tracking)
- Midpoint LIAS and left lateral condyle knee lateral on thigh (L_THIGH_LAT) (tracking)
- Midpoint R_THIGH_LAT and right lateral condyle anterior and center on thigh (R_THIGH_ANT) (tracking)
- Midpoint L_THIGH_LAT and left lateral condyle anterior and center on thigh (L_THIGH_ANT) (tracking)
- Right lateral condyle (RFLE)
- Left lateral condyle (LFLE)
- Right medial condyle (RFME) (can be used for calibration only)
- Left medial condyle (LFME) (can be used for calibration only)

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/iliac crest (RILI) (tracking only)
- Left lateral pelvic/iliac crest (LILI) (tracking only)

Thorax (6 markers):

- Spinous process C7 (CV7)
- Spinous process T10 (TV10)
- Superior jugular notch (SJN)
- Sternum xiphisternal joint (SXS)
- Right 10th rib (5 cm lateral to midline) (R10)

- Left 10th rib (5 cm lateral to midline) (L10)

Head (5 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 posterior head (RPH)
- Left posterior head (LPH)
- Aphex skull (SAS)

Upper arm segment (14 markers):

- Right acromion (RAC) (note: also used for orientation for thorax segment)
- Left acromion (LAC) (note: also used for orientation for thorax segment)
- 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):

- 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)

- Right head 2nd metacarpal (RHL5) – dorsal surface
- Left head 2nd metacarpal (LHL5) – dorsal surface

1080 Sprint (5 markers)

- Corner 1 (COR1) – top anterior R from behind
- Corner 2 (COR2) – top anterior L from behind
- Corner 3 (COR3) – top posterior R from behind
- Corner 4 (COR4) – top posterior L from behind
- Corner 5 (COR5) – bottom front

Feeding mechanism (3 markers)

- Height of feeder (TOP_FEED_1) – Top of feeder R from behind
- Height of feeder (TOP_FEED_2) – Top of feeder L from behind
- Bottom feeder (BOT_FEED_1) - Bottom of feeder R from behind
- Bottom feeder (BOT_FEED_C) – Bottom of feeder center
- Bottom feeder (BOT_FEED_2) - Bottom of feeder L from behind

- Feeder attachment to 1080 Sprint (1080_FEED) – proximal attachment of feeder to 1080 Sprint adjusted to hip height

Carabiner (1 marker)

Carabiner that is sliding on rope (CAR)

Appendix VI. Consent Form

Forespørsel om deltakelse i forskningsprosjektet

”Validitet av retningsforandringstester ved bruk av robotisk motstand”

Dette er et spørsmål til deg om å delta i et forskningsprosjekt hvor formålet er å undersøke reliabiliteten til retningsforandringstestser ved bruk av robotisk test- og treningsutstyr. I dette skrivet gir vi deg informasjon om målene for prosjektet og hva deltakelse vil innebære for deg.

FORMÅL

Retningsforandring er en grunnleggende egenskap for idrettslig prestasjonsevne, særlig i ballidretter. Per i dag finnes det er rekke tester som brukes for å teste retningsforandring som kategoriseres basert på varighet (< eller > 6 sekunder) eller antall retningsforandringer som gjennomføres. Dette fører til at det er vanskelig å sammenligne resultater mellom tester, samt at de også representerer ulike egenskaper som sprint løp og anaerob utholdenhet, og ikke retningsforandring. Derfor burde man bruke tester hvor retningsforandringen utgjør en stor del av målingen siden det vil gi trenere god informasjon om denne egenskapen. Det er en test som er kort og som inneholder en retningsforandring, 505 testen. Denne testen har blitt kritisert siden den inneholder kun en 180 graders retningsforandring. Dette er en viktig begrensning siden egenskapen for retningsforandring er avhengig av hvilken vinkel den utføres med samt at ballidretter stiller krav til retningsforandring i mange ulike retninger. Videre finnes det i dag ingen testprosedyrer for testing av retningsforandringer med motstand. Derfor ønsker vi i denne studien å undersøke reliabiliteten til utfallsmål for ulike 505 tester for retningsforandring med bruk av robotisk motstand.

Forsøkspersonene skal være friske kvinner og menn i alderen 16-35 år fra ulike ballidretter med erfaring fra styrketrening og eksplosiv testing av styrke. Prosjektet innebærer at du vil bli testet total seks ganger på tre ulike 505 tester med belastning.

HVA INNEBÆRER DELTAKELSE I STUDIEN?

Deltakere i denne studien skal gjennomføre seks testdager. Tre ulike retningsforandringstester med motstand vil bli testet to ganger. Disse testene inneholder en 5m akselerasjon med oppbremsing mot en retningsforandring (180 grader) med en påfølgende akselerasjon (5m). En av disse tre retningsforandringene skal gjennomføres per testdag med tre ulike motstander. Tre repetisjoner per motstand vil bli testet. Varigheten på en testdag er estimert til en time.

Alle deltakere vil få en økt innsikt i bruk av laboratoriemetoder som benyttes innen idrettsfag. Videre vil deltakere vil få nyttig informasjon om sin evne til retningsforandring som kan ha betydning for hvordan de vurdere sin egen treningsstatus, og hvordan de dermed kan planlegge eget treningsarbeid. I tillegg vil deltakere få økt kunnskap om hvilke vurderinger som er knyttet til hvordan man skal trene effektivt for å påvirke evnen til retningsforandring.

Mulige ulemper med deltakelsen i denne studien er at deltakerne selv må sette av tid til testing. Gjennomføring av testene innebærer alltid en viss risiko for skader, men det er ingen grunn til at denne risikoen er høyere ved deltakelse i denne studien enn ved egen trening og deltakelse i ballidrett. Testingen kan medføre midlertidig muskeltretthet og stølhet, men dette er ikke skadelig.

HVA SKJER MED INFORMASJONEN OM DEG?

Vi vil bare bruke opplysningene om deg til formålene vi har fortalt om i dette skrivet. Vi behandler opplysningene konfidensielt og i samsvar med personvernregelverket. Alle personopplysninger vil bli behandlet konfidensielt og uten navn og fødselsnummer eller andre direkte gjenkjennende opplysninger. Det betyr at resultatene blir ikke lagret under navnet, men med en kode. Navnet ditt blir derfor koblet til en kode som vil oppbevares i en safe ved NIH som kun to prosjektmedarbeidere har tilgang til. Etter prosjektslutt skal kodelisten slettes og dermed vil all data være anonymisert. Dine personopplysninger vil ikke kunne identifiseres i publikasjoner.

Prosjektet skal etter planen avsluttes 01.08.2021. Vi er pliktet til å oppbevare data og separat navneliste i 5 år etter sluttdato for etterprøvbarhet og kontroll av resultatene. Etter dette, altså 01.08.2026, vil all data i prosjektet slettes.

Prosjektleder har ansvar for den daglige driften av forskningsprosjektet og at opplysninger om deg blir behandlet på en sikker måte. Dine rettigheter: Så lenge du kan identifiseres i datamaterialet, har du rett til:

- innsyn i hvilke personopplysninger som er registrert om deg
- få rettet personopplysninger om deg
- få slettet personopplysninger om deg
- få utlevert en kopi av dine personopplysninger (dataportabilitet), og
- å sende klage til personvernombudet eller Datatilsynet om behandlingen av dine personopplysninger.

Hva gir oss rett til å behandle personopplysninger om deg?

Vi behandler opplysninger om deg basert på ditt samtykke.

På oppdrag fra Norges idrettshøgskole har NSD – Norsk senter for forskningsdata vurdert at behandlingen av personopplysninger i dette prosjektet er i samsvar med personvernregelverket.

FRIVILLIG DELTAKELSE

Der er frivillig å delta i prosjektet Hvis du velger å delta, undertegner du samtykkeerklæringen på siste side. Du kan når som helst og uten å oppgi noen grunn trekke ditt samtykke. Dersom du trekker deg fra prosjektet, kan du kreve å få slettet innsamlede prøver og opplysninger, med mindre opplysningene allerede er inngått i analyser eller brukt i vitenskapelige publikasjoner. Alle opplysninger om deg vil da bli anonymisert. Det vil ikke ha noen negative konsekvenser for deg hvis du ikke vil delta eller senere velger å trekke deg. Dersom du har spørsmål til studien, eller ønsker å benytte deg av dine rettigheter, ta kontakt med prosjektleder Ola Eriksrud (ola.eriksrud@nih.no/97617893), vårt personvernombud Karine Justad (personvernombud@nih.no), eller NSD – norsk senter for forskningsdata (personverntjenester@nsd.no / 55582117).

FORSIKRING

Alle deltakerne er forsikret ved at NIH som statlig institusjon er selvassurandør.

GODKJENNING

Studien er godkjent av intern etisk komite ved Norges idrettshøgskole.

SAMTYKKEERKLARING

Jeg har mottatt og forstått informasjon om prosjektet *Reliabilitet av retningsforandringstester ved bruk av robotisk motstand*, og har fått anledning til å stille spørsmål.

Jeg samtykker til:

å delta i prosjektet som er beskrevet ovenfor

at mine opplysninger behandles frem til prosjektet er avsluttet (ca. 01.08.2021) og lagres i 5 år etter prosjektslutt.

---------------------	--
Sted og dato	Deltakers eller foresattes signatur

Deltakers eller foresattes navn med trykte bokstaver

Appendix VII. Ethical Approval

Ola Eriksrud
Seksjon for fysisk prestasjonsevne   OSLO 03. september 2019

Søknad 101-290819 – Nye testmetoder for retningsforandring

Vi viser til søknad, prosjektbeskrivelse, informasjonsskriv og innsendt melding til NSD.
I henhold til retningslinjer for behandling av søknad til etisk komite for idrettsvitenskapelig forskning på mennesker, ble det i komiteens møte av 29. august 2019 konkludert med følgende:

Vedtak

På bakgrunn av forelagte dokumentasjon finner komiteen at prosjektet er forsvarlig og at det kan gjennomføres innenfor rammene av anerkjente etiske forskningsetiske normer nedfelt i NIHs retningslinjer. Til vedtaket har komiteen lagt følgende forutsetning til grunn:

- *Vilkår fra NSD følges*

Komiteen gjør oppmerksom på at vedtaket er avgrenset i tråd med fremlagte dokumentasjon. Dersom det gjøres vesentlige endringer i prosjektet som kan ha betydning for deltakernes helse og sikkerhet, skal dette legges fram for komiteen før eventuelle endringer kan iverksettes.

Med vennlig hilsen
Professor Sigmund Loland
Leder, Etisk komite, Norges idrettshøgskole

NSD Number: 148213

Construct validity of velocity measurements of a robotic resistance during change of direction

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Ola Eriksrud
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Keywords: Change of direction, kinematic analysis, phase analysis, performance, robotic resistance technology.

Note 1. Draft to be submitted to invitation to special issue here: https://www.frontiersin.org/research-topics/18304/maximal-neuromuscular-capacities-relevance-to-daily-function-and-athletic-performance?utm_source=F-RTM&utm_medium=CFP_E1&utm_campaign=PRD_CFP_T1_RT-TITLE

Abstract

The aim of this study was to determine construct validity of velocity measurements of a robotic resistance device during change of direction. After one familiarization session eight male (age: 22.1±4.2 yrs; weight: 83.3±17.1 kg; height: 181.6±12.6 cm) and three female subject (age: 21.7±1.5 yrs; weight: 69.7±2.4 kg; height: 167.0±3.6 cm) completed the modified 505 test (m505) with turning off the left and the right foot under three different loads (3, 6 and 9 kg) provided by a robotic resistance device (ROB). For all tests three-dimensional kinematic data was measured (200 Hz) using a full-body marker set with an additional marker (CAR) placed on the pulley used to attach the line from the robotic resistance device to the subject. Average velocity of overall center of mass (COM_{vel}), pelvis (COM_{pelvis_vel}) and pulley (CAR_{vel}) was then calculated and compared to the velocity obtained from ROB (ROB_{vel}) in .5 second intervals 1.5 seconds before and after change of direction. Average velocity from these intervals where compared using correlational and Bland Altman analysis, coefficient of variation (CV) and statistical parametric mapping (SPM). Mostly excellent correlations were observed for all comparisons and ranged from .93 to 1.00, .53 to 1.00 and .93 to 1.00 for the 3, 6 and 9 kg external load conditions respectively. CV ranged from .3 to 3.2, .8 to 4.3 and 1.5 to 7.7 for the CAR_{vel}, COM_{pelvis_vel} and COM_{vel} comparisons. The observed biases for CAR_{vel} comparisons ranged from -.027 to .05 m/s across all loaded conditions and time intervals, while ranged from -.246 to .128 m/s for the COM_{pelvis_vel} comparisons. The observed biases ranged from -.486 to .082 m/s when compared to COM_{vel}. SPM analysis yielded short time frames of significant difference to ROB_{vel} for COM_{vel} and COM_{pelvis_vel} only for all load conditions. The velocity measurements obtained by a robotic resistance device during a m505 test is valid as low biases, low CV´s and high correlations are observed for the ROB_{vel} to CAR_{vel} comparison. As single points of measurement (i.e. laser) is used to assess other athletic tasks (i.e. sprint running) the single point CAR_{vel} comparison is appropriate for the m505 test. The validity of velocity measurements during the m505 test provides researchers and coaches alike with new opportunities to further assess and understand this important athletic quality.

Introduction

Change of direction (CoD), “the skills and abilities needed to change movement direction, velocity or modes” (DeWeese & Nimphius, 2016), is an important skill in multidirectional sports (Bloomfield, Polman, & O'Donoghue, 2007; Sweeting, Aughey, Cormack, & Morgan, 2017; Young, Dawson, & Henry, 2015). Specifically, CoD ability is important in invasive sports (Young et al., 2015) to penetrate defensive lines (Fox, Spittle, Otago, & Saunders, 2014; Mohamad Zahidi & Ismail, 2018; Wheeler, Askew, & Sayers, 2010), create goal scoring opportunities (Faude, Koch, & Meyer, 2012), important quality in talent identification (Gil, Ruiz, Irazusta, Gil, & Irazusta, 2007), discriminate between levels of performance (Reilly, Williams, Nevill, & Franks, 2000) and draft selection in the National Football League (McGee & Burkett, 2003). Considering this importance of CoD in multidirectional sports it is imperative that we have good tests to quantify this important quality.

A CoD movement in its´s simplest form consist of different phases (acceleration to deceleration and re-acceleration) (Hader, Palazzi, & Buchheit, 2015). Currently a plethora of different tests are used to quantify this quality based on different movement patterns (i.e. sprint and side shuffle), angle of turn(s), number of turns and duration. Such differences makes comparisons between tests difficult as CoD is a task specific skill based on angle of turn and entry velocity (Dos'Santos, Thomas, Comfort, & Jones, 2018; Nimphius, Callaghan, Bezodis, & Lockie, 2017). Furthermore, overall time is the primary outcome variable. Then, especially in longer tests, overall time might not be representative of CoD, but rather anaerobic capacity and linear sprint ability (Vescovi & McGuigan, 2008). Considering that linear sprint and CoD performance are different qualities (Little & Williams, 2005) shorter tests, such as the modified 505 test (m505), which consist of two 5 m sprints with one 180 degree turn, might be a better representation of CoD performance (Nimphius et al., 2017). However, superior linear sprint capacity may still mask CoD ability even in shorter CoD tests (DeWeese & Nimphius, 2016; Nimphius et al., 2017). Consequently, measures such as the CoD deficit has been developed to better quantify CoD ability (Nimphius, Callaghan, Spiteri, & Lockie, 2016).

Based on the above shortcomings of CoD testing and the attempts to mitigate these (Nimphius et al., 2016), it has been advocated that CoD tests should quantify what happens during the tests. Specifically, measurements of center of mass (COM) velocity during CoD testing has been advocated (Nimphius et al., 2017). To obtain such measurements in a laboratory setting (i.e. motion capture) and calculate COM velocity is not difficult, but it is not practical and many cases not feasible for coaches and other practitioners in the applied setting. Field based technologies such as photocells (Buchheit, Haydar, & Ahmaidi, 2012; Nimphius et al., 2017), global navigation satellite systems (GNSS) and local positioning systems (LPS) technologies (Luteberget & Gilgien, 2020) and laser (Hader et al., 2015) have been used in the assessment of CoD ability. Photocells are commonly used to obtain overall time of the CoD test, but do not provide phase specific information (Buchheit et al., 2012). Furthermore, caution should be used if GNSS or LPS are to be used as they might have limited validity and reliability for short CoD tests (Buchheit et al., 2014; Luteberget & Gilgien, 2020). In a recent study Hader and co-workers designed a football specific field test based on two synchronized laser systems. This to explore phase specific information with different angular turns, which in turn could have practical implications if either acceleration to deceleration, re-acceleration or both should be specifically targeted in training (Hader et al., 2015). Such phase specific information is important considering that some athletes have been shown pace their run-up (acceleration to deceleration phase) based on the demand of the CoD (Nimphius, McGuigan, & Newton, 2013). This is in agreement with field based observations of the authors and colleagues. Without continuous measurements of athlete movement during a CoD test such phase specific information cannot be obtained.

Furthermore the ability to generate horizontal forces during both initial acceleration to deceleration and re-acceleration phases are important to CoD performance. During deceleration horizontally oriented braking forces are important to performance of the 505 tests (Dos'Santos, McBurnie, Thomas, Comfort, & Jones, 2020), while during acceleration the horizontal component of the ground reaction force is important to performance (Morin, Edouard, & Samozino, 2011). These are not surprising findings considering the impulse momentum relationship. Based on these finding and the high deceleration and acceleration demands in team sports (Harper, Carling, & Kiely, 2019) providing horizontal load prescription for training to improve CoD ability might be important. The importance of including horizontal unilateral movements on CoD ability was shown in a recent meta-analysis by Asadi and co-workers (Asadi, Arazi, Young, & de Villarreal, 2016). Recently, development of new technologies may provide us with an opportunity to obtain more detailed information about CoD testing in both lab and field based environments. Robotic resistance technologies (ROB) can be applied to CoD testing to provide continuous velocity measurement of the athlete and thereby provide phase specific information of CoD tests, while at the same time prescribe horizontal loading. With valid velocity measurements of both phases further analysis of deceleration as introduced by Harper and co-workers (Harper, Morin, Carling, & Kiely, 2020) can be explored in a CoD test. In addition, changes in momentum during CoD tests, as advocated for by others, can be explored (Nimphius et al., 2017). Robotic resistance technology has recently been applied for both linear sprint testing and training purposes (Lahti et al., 2020; Rakovic, Paulsen, Helland, Eriksrud, & Haugen, 2018; Rakovic, Paulsen, Helland, Haugen, & Eriksrud, 2020), but to the authors knowledge not applied to CoD testing. The aim of this study was to assess construct validity of the continuous velocity measurements of a robotic resistance device (ROB_{vel}). Specifically, compare ROB_{vel} to three-dimensional motion capture data used to calculate velocity of overall COM (COM_{vel}), pelvis COM (COM_{pelvis}) and to a marker placed on the carabiner (CAR), the point attachment to the athlete from the device.

Methods

Subjects

Eight male (age: 22.1±4.2 yrs; weight: 83.3±17.1 kg; height: 181.6±12.6 cm) and three female subject (age: 21.7±1.5 yrs; weight: 69.7±2.4 kg; height: 167.0±3.6 cm) with experience in ball sports (soccer (n=2), basketball (n=4) and handball (n=3), tennis (n=1) and floorball (n=1)) completed the study. Inclusion criteria were familiar with ball sports change of direction movements and no musculoskeletal or neurological injury within the past six months limiting sports participation for more than one week. The study was approved by the local Ethical committee and the National Data Protection Agency for Research (ref number: 148213), and conducted in accordance with the Declaration of Helsinki. Prior to participation all subjects, or legal guardian, provided a written informed consent after being given detailed verbal and written explanation of the purpose, procedures and risks associated with participation.

Procedures

All participants had one familiarization session prior to the test session as recommended for the modified 505-test (M505) (Barber, Thomas, Jones, McMahon, & Comfort, 2016). Anthropometric measurements (height and weight) were obtained prior to a standardized warm-up (jogging, forward and backward, side shuffle, lower extremity mobility exercises, jumps, sprint and two unloaded 505 tests on each foot) and lasted approximately 15 minutes. The same warm-up was used for both familiarization and test session.

Testing took place in the biomechanics laboratory at the Norwegian School of Sport Sciences where subjects performed two successful repetitions of the M505 tests with turns off both the left and right foot. Procedures have been described in detail previously (Draper & Lancaster, 1985; Taylor et al., 2019) but summarized here for clarity as it was performed under externally loaded conditions provided by a robotic resistance device. For all tests the subject started with a two-point start at a 5m mark (tape) from the center of the second force plate (tape mark on sides). The fiber cord from the robotic resistance device was attached to the subject using a carabiner onto a pulley (Cyclone 52; Purmotion, USA), which in turn was attached to a belt with two carabiners to a belt (1080 Vest; 1080 MAP AS, Oslo Norway). When turning off the left foot the carabiners were attached over the right hip and for right foot turns vice versa. This to ensure that the fiber cord from the resistance device was not in conflict with the movement. As the initial acceleration was toward the robotic resistance device this portion of the test was assisted with a greater demand placed on the deceleration and re-acceleration. A successful trial was defined as full effort with the penultimate and ultimate step hitting the floor mounted force plates. The external load protocol was 3, 9 and 6 kg with two successful turns off the left before the right foot for each loaded condition with the subject given a 2 minute rest between trials.

Equipment

Three-dimensional kinematic data was measured (200 Hz) using 15 Oqus (eight 700+ series, seven 400 series, Qualisys AB, Gothenburg, Sweden) of a full-body marker set (63 markers) with an additional marker (CAR) placed on the pulley used to attach the line from the robotic resistance device. Cameras had different vertical positions (wall and tripods) to ensure that they could capture markers for the entire recording volume. Two floor-mounted force plates SG-9 (Advanced Mechanical Technologies Inc., USA) were used to measure (1000 Hz) three-dimensional ground reaction forces of the penultimate and final contact step. Recorded analogue data were converted to digital data via an analogue-to-digital converter (USB-2533, Measurement Computing Corporation, USA). Prior to data acquisition the system was calibrated (60 seconds as recommended by the manufacturer) using an L-shaped reference frame (for the 750 mm 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 millimeters); and 3) if the T-shaped wand was subjectively judged to have not adequately covered the recording volume. The approximate recording volume was 5 m (length and width) and 2 m (height), and the laboratory coordinate frame was defined so that the y-axis was aligned with the initial running direction. A portable robotic resistance device (1080 Sprint; 1080 Motion, Lidingö, Sweden) was used to provide external resistance and measure time position, velocity and acceleration at 333 Hz. Specifically, velocity (ROB_{vel}) and acceleration (ROB_{acc}) is calculated as the first and second time derivative of position data respectively. The 1080 Sprint (ROB) has a servo motor (2000 RPM OMRON G5 Series Motor; OMRON Corp., Kyoto, Japan) that is attached to a carbon fiber spool around which a fiber cord is wrapped. The ROB device was positioned on a table 2 m behind the force plates and perpendicular to 505 running directions to allow for the m505 test to be performed along the global y-axis. The fiber cord was also passed through a feeder mechanism (0.95m behind force plate) that was adjusted to hip height (greater trochanter) of each subject (Figure 1). The loads used was 3, 6 and 9 kg. The auto start function of the robotic resistance device was used (onset of measurement with speed > 0.2 m/s) (Rakovic et al., 2020) .

Data analysis

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, 2014 #729}; 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, Biagi, Merlo, Belvedere, & Benedetti, 2011; Wu et al., 2002); 5) thorax (Leardini et al., 2011; Wu et al., 2005); and 6) upper arm, forearm and hand (Wu et al., 2005) (Visual 3D® (C-Motion Inc., Rockville, MD, USA). Then, overall center of mass (COM) and pelvis (COM_{pelvis}) was calculated from segmental COM data. Velocity for CAR, COM, and COM_{pelvis} was then calculated as first time derivative of position data (CAR_{vel}, COM_{vel} and COM_{pelvis_vel}). Only the y-components of these variables were used, since the y-axis was aligned with the m505 running direction.

As ROB_{vel} data is already filtered CAR_{vel}, COM_{vel} and COM_{pelvis_vel} were filtered using first order discrete Tustin lowpass filter with a filter coefficient of 0.04 sec. Then, motion capture data (CAR_{vel}, COM_{vel} and COM_{pelvis_vel}) was synchronized to ROB_{vel}. Specifically, ROB_{vel} data was synchronized to CAR_{vel} data as it represents movement of the point of attachment from the robotic resistance device to the subject. A cross correlation between CAR_{vel} and ROB_{vel} was done to determine time offset with a subsequent time shift of data based on the greatest correlation.

As different definitions of time of change of direction are used (Clarke, Read, De Ste Croix, & Hughes, 2020; Sayers, 2015) or not defined (Hader et al., 2015), the authors defined time of change of direction based on counter-movement jump definitions (McMahon, Suchomel, Lake, & Comfort, 2018). Specifically, time of change of direction was defined as the time when direction of ROB_{vel} changed (ROB_{vel_COD}). Then, velocity (ROB_{vel}, CAR_{vel}, COM_{vel} and COM_{pelvis_vel}) at 0.1 second time intervals before (-) and (+) after ROB_{vel_COD} were defined. Also, average velocity for 0.1, 0.5, 1.0 and 1.5 second intervals before (-) and after (+) ROB_{vel_COD} were also calculated for all outcome variables (ROB_{vel}, CAR_{vel}, COM_{vel} and COM_{pelvis_vel}). In addition the following performance outcome measurements were obtained from the robotic resistance device for the m505 test: total time ($m505_{time}$), total distance ($m505_{dist}$), time phase 1a ($m505_{1a\_time}$), distance 1a ($m505_{1a\_dist}$), average velocity phase 1a ($m505_{1a\_avgvel}$), time phase 1b ($m505_{1b\_time}$), distance 1b ($m505_{1b\_dist}$) and average velocity phase 1b ($m505_{1b\_avgvel}$).

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 Shapiro Wilk´s test ($p<0.05$). The criterion related (concurrent) validity of the robotic resistance device was determined by comparing ROB_{vel}, CAR_{vel}, COM_{vel} and COM_{pelvis_vel} measurements during different time intervals using correlational analysis, Pearson product moment correlation (r) and spearman rank order correlation (ρ), for normal and non-normal distribution respectively. Interpretation of correlation coefficients was done according to the guidelines of Portney and Watkins (Portney & Watkins, 1993). Correlation coefficients (CV) was performed using custom spreadsheets (Hopkins, 2015). Then, Bland Altman method was employed to determine bias and limits of agreement for the different time intervals as defined previously. Furthermore, statistical parametric mapping (SPM) (Pataky, Vanrenterghem, & Robinson, 2015) using unpaired sample t-tests (SPM(t);$\alpha<0.05$; two-tailed) was used to determine if velocity from ROB (ROB_{vel}) was different from kinematic data (CAR_{vel}, COM_{pelvis_vel} and COM_{vel}) one second before (-) and after (+) CoD for the different load conditions.

Results

A total of 40, 40 and 44 tests were analyzed for the 3, 6 and 9kg loaded conditions respectively. Performance on the m505 tests, average left and right turns, ranged from 3.26 to 3.52 sec for the different loaded conditions. Phase specific times ranged 1.77 to 1.83 sec and

1.47 to 1.69 sec for phase 1a and 1b respectively for the different loaded conditions (Table 1).

Xxx Insert Table 1 about here xxxx

All correlations between ROB_{vel} and CAR_{vel}, COM_{pelvis_vel} and COM_{vel} were mostly good to excellent. Specifically, correlation coefficients between ROB_{vel} and the other outcome variables ranged from .93 to 1.00, .53 to 1.00 and .93 to 1.00 for 3, 6 and 9 kg external load respectively (Table 2). CV ranged from .3 to 3.2, .8 to 4.3 and 1.5 to 7.7 for the CARvel, COM_{pelvis_vel} and COM_{vel} comparisons. The observed biases for CAR_{vel} comparisons ranged from -.027 to .05 m/s across all loaded conditions and time intervals, while ranged from -.246 to .128 m/s for the COM_{pelvis_vel} comparisons. The observed biases ranged from -.486 to .082 m/s when compared to COM_{vel} (Table 2). Bland Altman analyses for the same time intervals (0.5 sec) are presented in Figure 1-3 for the 3, 6 and 9 kg conditions respectively. Results for all time intervals are presented in Appendix I, II and III for the 3, 6, and 9 kg loaded conditions respectively.

Xxxx Insert Table 2 about here xxxx

Xxxx Insert Figure 1 about here xxxx

Xxxx Insert Figure 2 about here xxxx

Xxxx Insert Figure 3 about here xxxx

SPM analysis yielded no significant difference between ROB_{vel} and CAR_{vel} for the different load conditions. However, significant underestimation from .3174 to .3551 seconds for the COM_{pelvis_vel} comparison was observed for the 3 kg load condition. For the 6 kg load condition significant overestimation from -.0565 to .2225 seconds and underestimation from .2718 to .3575 seconds for the COM_{vel} comparison were observed, and a significant underestimation from .2718 to .3575 for the COM_{pelvis_vel} comparison. For the 9 kg load condition significant overestimation from -.5166 to -.4056 seconds and underestimation from .8129 to .8888 seconds for the COM_{vel} comparison were observed, and a significant underestimation from .3051 to .4193 for the COM_{pelvis_vel} comparison (Figure 4-6)

Xxxx Insert Figure 4 about here xxxx
Xxxx Insert Figure 5 about here xxxx
Xxxx Insert Figure 6 about here xxxx

Discussion

The robotic resistance device provide valid velocity measurements of an athlete performing a m505 test under different loaded conditions. The mostly excellent correlation coefficients and small CV values indicate a close relationship with ROB_{vel} and the other outcome variables. Furthermore, this excellent relationship is maintained for the different loaded conditions. The observed biases differ when ROB_{vel} is compared to CAR_{vel}, COM_{pelvis_vel} and COM_{vel} for the different time intervals. Specifically, when ROB_{vel} is compared to CAR_{vel} the observed biases are small for all time intervals, while they increase when compared to COM_{pelvis_vel} and COM_{vel}.

These greater observed biases can be explained by the different COM calculations from kinematic data.

The same robotic resistance device has been compared to timing gate measurements previously in sprint running (Rakovic et al., 2020). The outcome measurements in that study was split time measurements with correlations ranging from .48 to .95. Overall, better correlations where observed in the current study as they were excellent with one exception (ρ=.53) for the ROB_{vel} to COM_{vel} comparison for the $t_{1.0 \text{ to } 1.5}$ time interval with 6 kg external load. As we did not remove any outliers in this study (Hoaglin, Iglewicz, & Tukey, 1986), and that a total of 13 tests were compared for this time interval, one variable may have a greater effect on the correlation coefficient. In fact, the trials included for the different time intervals varies (Table 2). Trials included for the time intervals one second prior to and after the change of direction included a large percentage of total tests done and ranged from 38 to 44 tests. However, for the time intervals 1.5 to 1.0 s before and after change of direction the number of tests analyzed ranged from 8 to 22 tests. The reason for the lower number of tests included for these time intervals is due to the quality of kinematic data. The recording volume included the start and end position of the m505 test, but there were challenges getting good quality kinematic data of markers necessary for the analysis. This might be due to fewer cameras being able to observe all markers at the start and the end of the test. Furthermore, the above is also the reason why the SPM analysis was employed for one second before and after change of direction. In addition, the reason for selecting 1.5 seconds pre and post change of direction was that others have found total m505 test times to be in the range of 2-3 seconds (Nimphius et al., 2017).

The observed biases differed between comparisons with smallest found between ROB_{vel} and CAR_{vel} (Table 2, Figure 1-3). The same device yield small observed biases and within the limits of precision of +/- 0.01s for linear sprint running for most time intervals with the exception of the 0-5m intervals, which were explained by differences in the onset of measurement. If the average five meter split times (from 5 to 20 m) from that study is converted to velocity with and without the observed bias the velocity bias range from 0.011 to 0.082 m/s. Granted the average velocity is greater for these intervals than those observed in the current study, but it provides a reference for the observed biases. Based on these values the observed biases for the CAR_{vel} comparison are smaller, the COM_{pelvis_vel} comparison comparable, while the COM_{vel} comparison have greater biases. The greater observed biases for the COM_{pelvis} and COM can be explained by the fact that they are based on calculations from multiple markers on the pelvis and whole body respectively. Especially COM_{vel} calculations are subject to both upper and lower extremity movements, which are not measured by the robotic resistance device as the point of attachment to the subject is by a pelvic belt. Thus, the CAR comparison is a better representation of the validity of the velocity measurements of the robotic resistance device. In fact, in linear sprint both laser and radar are accepted measures of athlete movement and used for validation (Jimenez-Reyes et al., 2019) purposes. Laser measurements of linear sprint is based on one point, or a moving point, on the backside of the athlete performing the sprint, which is similar to the CAR_{vel} measurement in in current study.

Overall time of the subjects on m505 test is slightly slower (Table 1) than that presented elsewhere (Nimphius et al., 2017). Obviously external load will impact time, especially in the re-acceleration phase and thereby influencing overall time. However, the observed standard deviations for overall time for different loaded conditions (range from .29 to .35 seconds) indicate a fairly wide distribution of performances on the m505 test. This ensures validity over a greater range of performances. Furthermore, the inclusion of both males and females as well as different sports (soccer, basketball, handball, tennis and floorball) further improves validity to encompass different ball sports and gender. However, phase specific comparisons of measurements (time, distance and average velocity) have not been done as the authors are unaware of such information being reported elsewhere.

Phase specific information on a football specific change of direction test has been explored by Hader and co-authors with the use of laser guns (Hader et al., 2015). However, only overall time was validated against timing gates, while reliability was quantified for phase specific information (peak speed and acceleration, distance at peak speed, peak deceleration, distance at peak deceleration, minimum speed and speed from 8to 12 m). In their study typical error, and not CV, was reported along with bias and correlations as their validity measures. This makes comparisons to the observed CV values in this study difficult, while the reported correlations were similar to those observed in the current study.

Limitations

Kinematic data for all subjects for the full m505 test would have allowed for more comparisons to ROB_{vel}, especially the 1.5 to 1.0 second interval before and after the change of direction (Table 2). In addition, one could then have expanded the analysis to include the full test and not limited it to 1.5 seconds before and after the change of direction. Furthermore, ROB_{vel} and kinematic data were synchronized by cross correlation in post processing, which may have impacted our results. However, from the mostly excellent correlations, small CV values and biases for the CAR_{vel} comparison it appears that the continuous velocity measurements obtained by the robotic resistance device is a valid representation of subject velocity during a m505 test.

Conclusion

The velocity measurements obtained by a robotic resistance device during a m505 test is valid as low biases, low CV´s and high correlations are observed for the ROB_{vel} to CAR_{vel} comparison. The increased observed biases and lower CV values for the COM_{vel} and COM_{pelvis_vel} comparisons is to be expected as the robotic resistance device represent movement of the point of attachment to the athlete, especially for the COM_{vel} comparison as the kinematic methods used quantifies upper and lower extremity movement during the test. As single points of measurement (i.e. laser) is used to assess other athletic tasks (i.e. sprint running) the single point CAR_{vel} comparison is appropriate for the m505 test. The validity of velocity measurements during the m505 test provides researchers and coaches alike with new opportunities to further assess and understand this important athletic quality.

Practical applications

Our findings has the potential to influence not only field, but also lab based testing and training of change of direction. In fact, continuous and phase specific information (time, distance, average velocity) can provide coaches with important information that previously only was available in a lab setting. In turn, such information can be used to target a specific phase or both in training with the use of horizontal loading. Furthermore, velocity development during a m505 tests may allow for calculation of change of momentum during the test and thereby increase our understanding of this important quality in a much more time efficient manner (Nimphius et al., 2017). In addition, further exploration of deceleration performance based on the methods described by Harper and co-authors (Harper et al., 2020) can be employed on a change of direction test such at the m505.

Author Contributions

All authors contributed to the data collection, interpretation and revising the manuscript. The original study design was made by OE and ØG and discussed with FA.

Conflict of interest statement

OE is a shareholder in 1080 Motion AB

References

Asadi, A., Arazi, H., Young, W. B., & de Villarreal, E. S. (2016). The Effects of Plyometric Training on Change-of-Direction Ability: A Meta-Analysis. *International Journal of Sports Physiology and Performance, 11*(5), 563-573. doi:10.1123/ijspp.2015-0694

Barber, O. R., Thomas, C., Jones, P. A., McMahon, J. J., & Comfort, P. (2016). Reliability of the 505 Change-of-Direction Test in Netball Players. *Int J Sports Physiol Perform, 11*(3), 377-380. doi:10.1123/ijspp.2015-0215

Bell, A. L., Brand, R. A., & Pedersen, D. R. (1989). Prediction of hip joint centre location from external landmarks. *Human movement science, 8*, 3-16.

Bloomfield, J., Polman, R., & O'Donoghue, P. (2007). Physical Demands of Different Positions in FA Premier League Soccer. *J Sports Sci Med, 6*(1), 63-70.

Buchheit, M., Haydar, B., & Ahmaidi, S. (2012). Repeated sprints with directional changes: do angles matter? *J Sports Sci, 30*(6), 555-562. doi:10.1080/02640414.2012.658079

Buchheit, M., Samozino, P., Glynn, J. A., Michael, B. S., Al Haddad, H., Mendez-Villanueva, A., & Morin, J. B. (2014). Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. *J Sports Sci, 32*(20), 1906-1913. doi:10.1080/02640414.2014.965191

Clarke, R., Read, P. J., De Ste Croix, M. B. A., & Hughes, J. D. (2020). The Deceleration Deficit: A Novel Field-Based Method to Quantify Deceleration During Change of Direction Performance. *J Strength Cond Res*. doi:10.1519/JSC.0000000000003856

DeWeese, B., & Nimphius, S. (2016). Speed and agility program design and technique. In N. T. Triplett & G. G. Haff (Eds.), *Essentials of Strength and Conditioning* (pp. 521-557). Champaign, IL, USA: Human Kinetics.

Dos'Santos, T., McBurnie, A., Thomas, C., Comfort, P., & Jones, P. A. (2020). Biomechanical Determinants of the Modified and Traditional 505 Change of Direction Speed Test. *Journal of Strength and Conditioning Research, 34*(5), 1285-1296. doi:10.1519/Jsc.0000000000003439

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2018). The Effect of Angle and Velocity on Change of Direction Biomechanics: An Angle-Velocity Trade-Off. *Sports Med, 48*(10), 2235-2253. doi:10.1007/s40279-018-0968-3

Draper, J. A., & Lancaster, M. G. (1985). The 505 test: A test for agility in the horizontal plane. *Australian Journal of Science and Medicine, 17*, 15-18.

Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *J Sports Sci, 30*(7), 625-631. doi:10.1080/02640414.2012.665940

Fox, A., Spittle, M., Otago, L., & Saunders, N. (2014). Offensive Agility Techniques Performed During International Netball Competition. *International Journal of Sports Science & Coaching, 9*(3), 543-552. doi:Doi 10.1260/1747-9541.9.3.543

Gil, S., Ruiz, F., Irazusta, A., Gil, J., & Irazusta, J. (2007). Selection of young soccer players in terms of anthropometric and physiological factors. *J Sports Med Phys Fitness, 47*(1), 25-32.

Hader, K., Palazzi, D., & Buchheit, M. (2015). Change of Direction Speed in Soccer: How Much Braking Is Enough? *Kinesiology, 47*(1), 67-74.

Harper, D. J., Carling, C., & Kiely, J. (2019). High-Intensity Acceleration and Deceleration Demands in Elite Team Sports Competitive Match Play: A Systematic Review and Meta-Analysis of Observational Studies. *Sports Med, 49*(12), 1923-1947. doi:10.1007/s40279-019-01170-1

Harper, D. J., Morin, J. B., Carling, C., & Kiely, J. (2020). Measuring maximal horizontal deceleration ability using radar technology: reliability and sensitivity of kinematic and kinetic variables. *Sports Biomech*, 1-17. doi:10.1080/14763141.2020.1792968

Hoaglin, D. C., Iglewicz, B., & Tukey, J. W. (1986). Performance of Some Resistant Rules for Outlier Labeling. *Journal of the American Statistical Association, 81*(396), 991-999. doi:Doi 10.2307/2289073

Hopkins, W. G. (2015). Spreadsheets for Analysis of Validity and Reliability. *Sportscience, 19*, 36-42.

Jimenez-Reyes, P., Cross, M., Ross, A., Samozino, P., Brughelli, M., Gill, N., & Morin, J. B. (2019). Changes in mechanical properties of sprinting during repeated sprint in elite rugby sevens athletes. *European Journal of Sport Science, 19*(5), 585-594. doi:10.1080/17461391.2018.1542032

Lahti, J., Jimenez-Reyes, P., Cross, M. R., Samozino, P., Chassaing, P., Simond-Cote, B., . . . Morin, J. B. (2020). Individual Sprint Force-Velocity Profile Adaptations to In-Season Assisted and Resisted Velocity-Based Training in Professional Rugby. *Sports (Basel), 8*(5). doi:10.3390/sports8050074

Leardini, A., Biagi, F., Merlo, A., Belvedere, C., & Benedetti, M. G. (2011). Multi-segment trunk kinematics during locomotion and elementary exercises. *Clinical biomechanics, 26*(6), 562-571. doi:10.1016/j.clinbiomech.2011.01.015

Little, T., & Williams, A. G. (2005). Specificity of acceleration, maximum speed, and agility in professional soccer players. *J Strength Cond Res, 19*(1), 76-78. doi:10.1519/14253.1

Luteberget, L. S., & Gilgien, M. (2020). Validation methods for global and local positioning-based athlete monitoring systems in team sports: a scoping review. *BMJ Open Sport Exerc Med, 6*(1), e000794. doi:10.1136/bmjsem-2020-000794

McGee, K. J., & Burkett, L. N. (2003). The National Football League combine: a reliable predictor of draft status? *J Strength Cond Res, 17*(1), 6-11. doi:10.1519/1533-4287(2003)017<0006:tnflca>2.0.co;2

McMahon, J. J., Suchomel, T. J., Lake, J. P., & Comfort, P. (2018). Understanding the Key Phases of the Countermovement Jump Force-Time Curve. *Strength and Conditioning Journal, 40*(4), 96-106. doi:10.1519/Ssc.0000000000000375

Mohamad Zahidi, N. N., & Ismail, S. I. (2018). Notational analysis of evasive agility skills executed by attacking ball carriers among elite rugby players of the 2015 Rugby World Cup. *Movement, Health & Exercise, 7*(1), 99-113.

Morin, J. B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Med Sci Sports Exerc, 43*(9), 1680-1688. doi:10.1249/MSS.0b013e318216ea37

Nimphius, S., Callaghan, S. J., Bezodis, N. E., & Lockie, R. G. (2017). Change of Direction and Agility Tests: Challenging Our Current Measures of Performance. *J Strength.Cond.Res., 40*(1), 1-13.

Nimphius, S., Callaghan, S. J., Spiteri, T., & Lockie, R. G. (2016). Change of Direction Deficit: A More Isolated Measure of Change of Direction Performance Than Total 505 Time. *J Strength Cond Res, 30*(11), 3024-3032. doi:10.1519/JSC.0000000000001421

Nimphius, S., McGuigan, M. R., & Newton, R. U. (2013). Is there a pacing strategy during a 505 change of direction test in adolescents? *Journal of strength and conditioning research / National Strength & Conditioning Association, 27*.

Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2015). Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *J Biomech, 48*(7), 1277-1285. doi:10.1016/j.jbiomech.2015.02.051

Portney, L. G., & Watkins, M. P. (1993). *Foundations to clinical research applications to practice*. Stamford, CT, USA: Appleton & Lange.

Rakovic, E., Paulsen, G., Helland, C., Eriksrud, O., & Haugen, T. (2018). The effect of individualised sprint training in elite female team sport athletes: A pilot study. *J Sports Sci, 36*(24), 2802-2808. doi:10.1080/02640414.2018.1474536

Rakovic, E., Paulsen, G., Helland, C., Haugen, T., & Eriksrud, O. (2020). Validity and reliability of a robotic resistance device. *J Strength.Cond.Res., Pre print*.

Reilly, T., Williams, A. M., Nevill, A., & Franks, A. (2000). A multidisciplinary approach to talent identification in soccer. *J Sports Sci, 18*(9), 695-702. doi:10.1080/02640410050120078

Sayers, M. G. L. (2015). Influence of Test Distance on Change of Direction Speed Test Results. *Journal of Strength and Conditioning Research, 29*(9), 2412-2416. doi:10.1519/Jsc.0000000000001045

Sweeting, A. J., Aughey, R. J., Cormack, S. J., & Morgan, S. (2017). Discovering frequently recurring movement sequences in team-sport athlete spatiotemporal data. *J Sports Sci, 35*(24), 2439-2445. doi:10.1080/02640414.2016.1273536

Taylor, J. M., Cunningham, L., Hood, P., Thorne, B., Irvin, G., & Weston, M. (2019). The reliability of a modified 505 test and change-of-direction deficit time in elite youth football players. *Science and Medicine in Football, 3*(2), 157-162. doi:10.1080/24733938.2018.1526402

Vescovi, J. D., & McGuigan, M. R. (2008). Relationships between sprinting, agility, and jump ability in female athletes. *J Sports Sci, 26*(1), 97-107. doi:10.1080/02640410701348644

Wheeler, K. W., Askew, C. D., & Sayers, M. G. (2010). Effective attacking strategies in rugby union. *European Journal of Sport Science, 10*(4), 237-242. doi:Pii 922926421
10.1080/17461391.2010.482595

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., . . . Stokes, I. (2002). ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine. International Society of

Biomechanics. *Journal of biomechanics, 35*(4), 543-548. doi:10.1016/S0021-9290(01)00222-6

Wu, G., van der Helm, F. C., Veeger, H. E., Makhsous, M., Van Roy, P., Anglin, C., . . . International Society of, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand. *J Biomech, 38*(5), 981-992. doi:10.1016/j.jbiomech.2004.05.042

Young, W. B., Dawson, B., & Henry, G. J. (2015). Agility and Change-of-Direction Speed are Independent Skills: Implications for Training for Agility in Invasion Sports. *International Journal of Sports Science & Coaching, 10*(1), 159-169. doi:Doi 10.1260/1747-9541.10.1.159

Figures

Figure 1. Agreement analysis of velocity data from the robotic resistance device (ROB_{vel}) and kinematic variables (CAR_{vel}, COM_{pelvis_vel} and COM_{vel}) for 0.5 second time intervals before (-) and after CoD with 3 kg load. Bland Altman plots (y axis: difference score and x-axis: mean score) with fixed bias (full line), 95% confidence interval (dotted line) and agreement (dashed line).

Figure 2. Agreement analysis of velocity data from the robotic resistance device (ROB_{vel}) and kinematic variables (CAR_{vel}, COM_{pelvis_vel} and COM_{vel}) for 0.5 second time intervals before (-) and after CoD with 6 kg load. Bland Altman plots (y axis: difference score and x-axis: mean score) with fixed bias (full line), 95% confidence interval (dotted line) and agreement (dashed line).

Figure 3. Agreement analysis of velocity data from the robotic resistance device (ROB_{vel}) and kinematic variables (CAR_{vel}, COM_{pelvis_vel} and COM_{vel}) for 0.5 second time intervals before (-) and after CoD with 9 kg load. Bland Altman plots (y axis: difference score and x-axis: mean score) with fixed bias (full line), 95% confidence interval (dotted line) and agreement (dashed line).

Figure 4. SPM results with 3 kg load one second pre and post CoD (x-axis all graphs). ROB_{vel} is compared to COM_{vel} (left column), COM_{pelvis_vel} (middle column) and CAR_{vel} (right column). Upper row shows average ROB_{vel} (blue line) with 95 % confidence interval (blue shade) and average COM_{vel}, COM_{pelvis_vel} and CAR_{vel} (red line) with 95% confidence (red shade). Middle row shows average velocity difference (blue line) with 95% confidence interval (blue shade) for the different comparisons. Bottom row shows SPM(t) comparisons with t-value on y-axis and 95% confidence interval (red dotted line) with significant underestimation from .3174 to .3551 seconds for the COM_{pelvis_vel} comparison.

Figure 5. SPM results with 6 kg load one second pre and post CoD (x-axis all graphs). ROB_{vel} velocity is compared to COM_{vel} (left column), COM_{pelvis_vel} (middle column) and CAR_{vel} (right column). Upper row shows average ROB_{vel} (blue line) with 95 % confidence interval (blue shade) and average COM_{vel}, COM_{pelvis_vel} and CAR_{vel} (red line) with 95% confidence (red shade). Middle row shows average velocity difference (blue line) with 95% confidence interval (blue shade) for the different comparisons. Bottom row shows SPM(t) comparisons with t-value on y-axis and 95% confidence interval (red dotted line) with significant overestimation from -.0565 to .2225 seconds and underestimation from .2718 to .3575 seconds for the COM_{vel} comparison. Significant underestimation from .2718 to .3575 for the COM_{pelvis_vel} comparison.

Figure 6. SPM results with 9 kg load one second pre and post CoD (x-axis all graphs). ROB_{vel} is compared to COM_{vel} (left column), COM_{pelvis_vel} (middle column) and CAR_{vel} (right column). Upper row shows average ROB_{vel} (blue line) with 95 % confidence interval (blue shade) and average COM_{vel}, COM_{pelvis_vel} and CAR_{vel} (red line) with 95% confidence (red shade). Middle row shows average velocity difference (blue line) with 95% confidence interval (blue shade) for the different comparisons. Bottom row shows SPM(t) comparisons with t-value on y-axis and 95% confidence interval (red dotted line) with significant overestimation from -.5166 to -.4056 seconds and underestimation from .8129 to .8888 seconds for the COM_{vel} comparison. Significant underestimation from .3051 to .4193 for the COM_{pelvis_vel} comparison.

Tables

Table 1. m505 test results for the different loaded conditions

Table 2. Agreement and correlation analysis of 0.5 second intervals

Figure 1

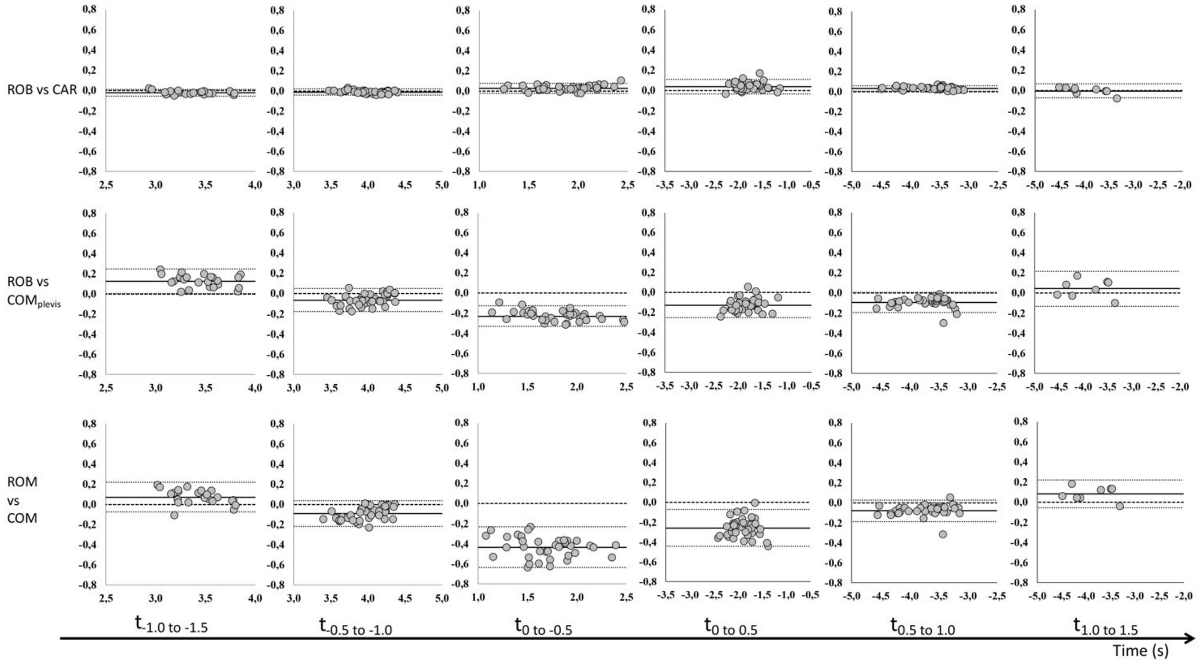
ROB vs CAR
ROB vs COMplevis
ROM vs COM
0,8
0,6
0,4
0,2
0,0
-0,2
-0,4
-0,6
-0,8
2,5 3,0 3,5 4,0
3,0 3,5 4,0 4,5 5,0
1,0 1,5 2,0 2,5
-3,5 -3,0 -2,5 -2,0 -1,5 -1,0 -0,5
-5,0 -4,5 -4,0 -3,5 -3,0 -2,5
-5,0 -4,5 -4,0 -3,5 -3,0 -2,5 -2,0
t-1.0 to -1.5
t-0.5 to -1.0
t0 to -0.5
t0 to 0.5
t0.5 to 1.0
t1.0 to 1.5
Time (s)

Figure 2

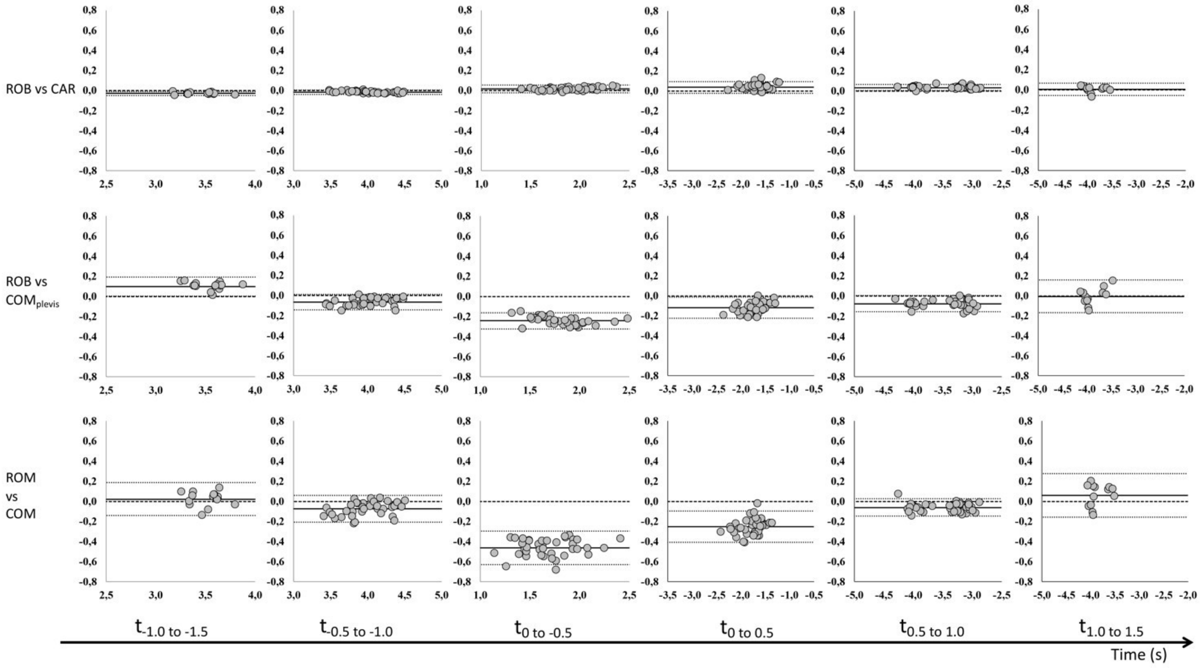
ROB vs CAR
ROB vs COM$_{plevis}$
ROM vs COM
0,8
0,6
0,4
0,2
0,0
-0,2
-0,4
-0,6
-0,8
2,5 3,0 3,5 4,0
3,0 3,5 4,0 4,5 5,0
1,0 1,5 2,0 2,5
-3,5 -3,0 -2,5 -2,0 -1,5 -1,0 -0,5
-5,0 -4,5 -4,0 -3,5 -3,0 -2,5
-5,0 -4,5 -4,0 -3,5 -3,0 -2,5 -2,0
$t_{-1.0\ \text{to}\ -1.5}$
$t_{-0.5\ \text{to}\ -1.0}$
$t_{0\ \text{to}\ -0.5}$
$t_{0\ \text{to}\ 0.5}$
$t_{0.5\ \text{to}\ 1.0}$
$t_{1.0\ \text{to}\ 1.5}$
Time (s)

Figure 3

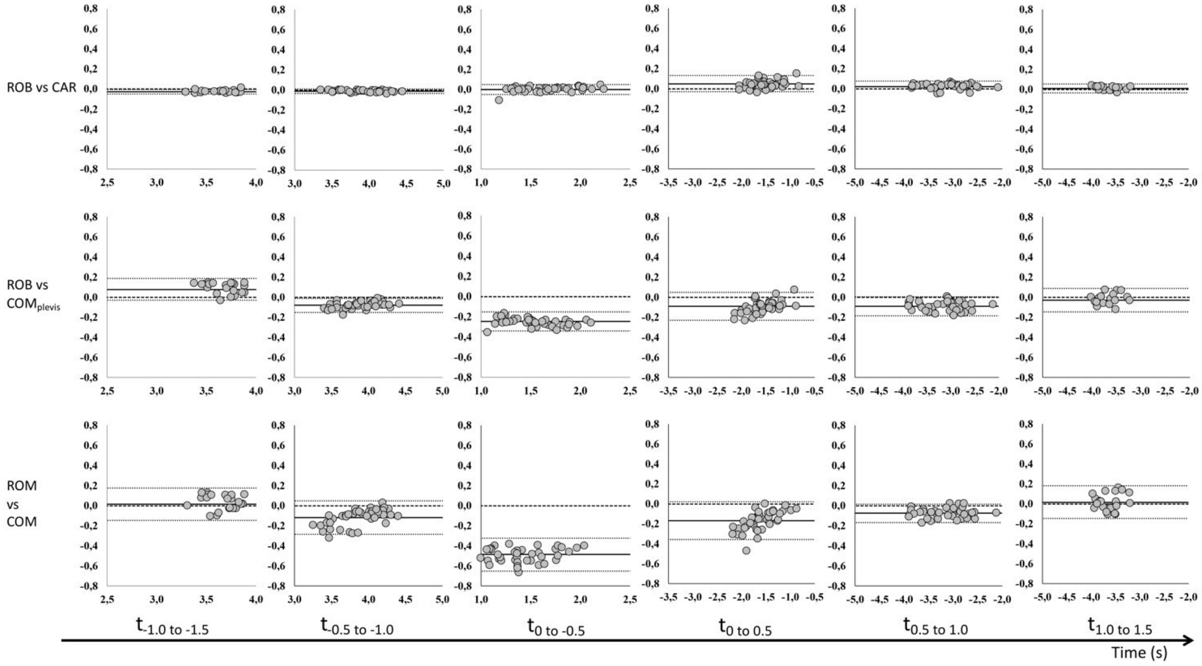
ROB vs CAR
ROB vs COM$_{plevis}$
ROM vs COM
0,8
0,6
0,4
0,2
0,0
-0,2
-0,4
-0,6
-0,8
2,5 3,0 3,5 4,0
3,0 3,5 4,0 4,5 5,0
1,0 1,5 2,0 2,5
-3,5 -3,0 -2,5 -2,0 -1,5 -1,0 -0,5
-5,0 -4,5 -4,0 -3,5 -3,0 -2,5 -2,0
-5,0 -4,5 -4,0 -3,5 -3,0 -2,5 -2,0
$t_{-1.0 \text{ to } -1.5}$
$t_{-0.5 \text{ to } -1.0}$
$t_{0 \text{ to } -0.5}$
$t_{0 \text{ to } 0.5}$
$t_{0.5 \text{ to } 1.0}$
$t_{1.0 \text{ to } 1.5}$
Time (s)

Figure 4

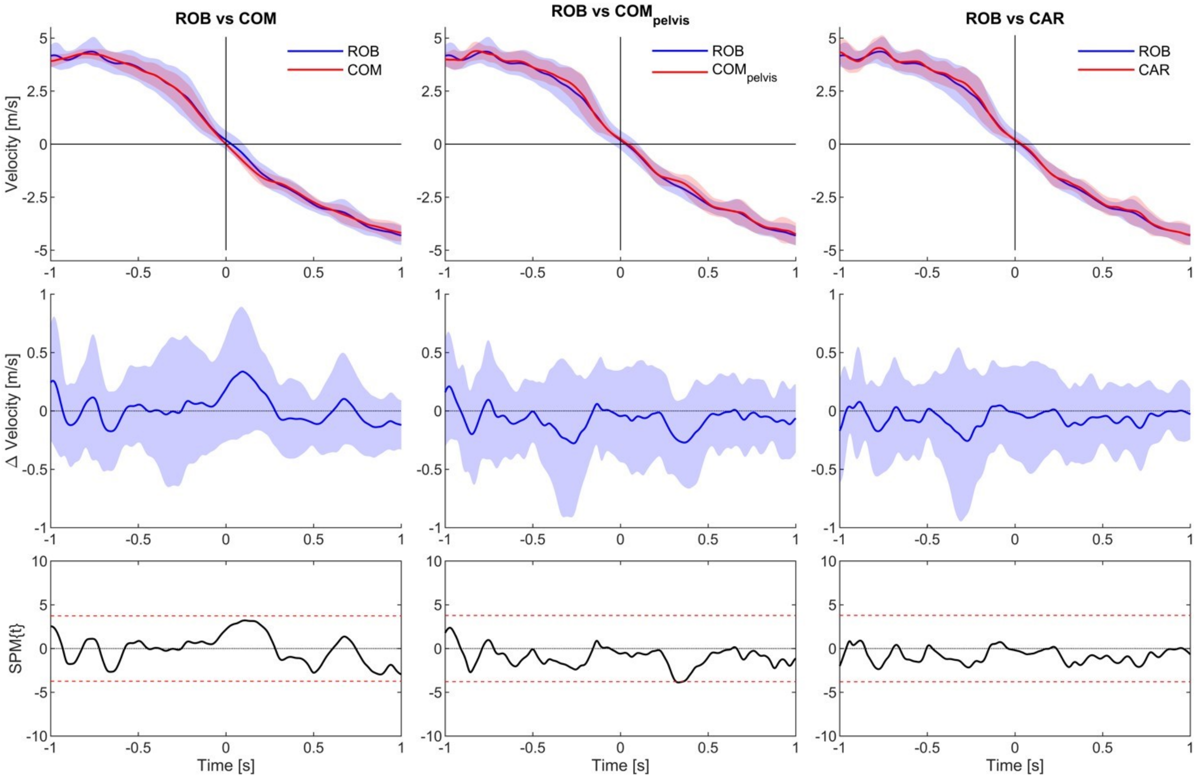
ROB vs COM
ROB vs $\text{COM}_{\text{pelvis}}$
ROB vs CAR
ROB
COM
$\text{COM}_{\text{pelvis}}$
CAR
Velocity [m/s]
Δ Velocity [m/s]
SPM{t}
Time [s]
5
2.5
0
-2.5
-5
1
0.5
-0.5
-1
10
-10

Figure 5

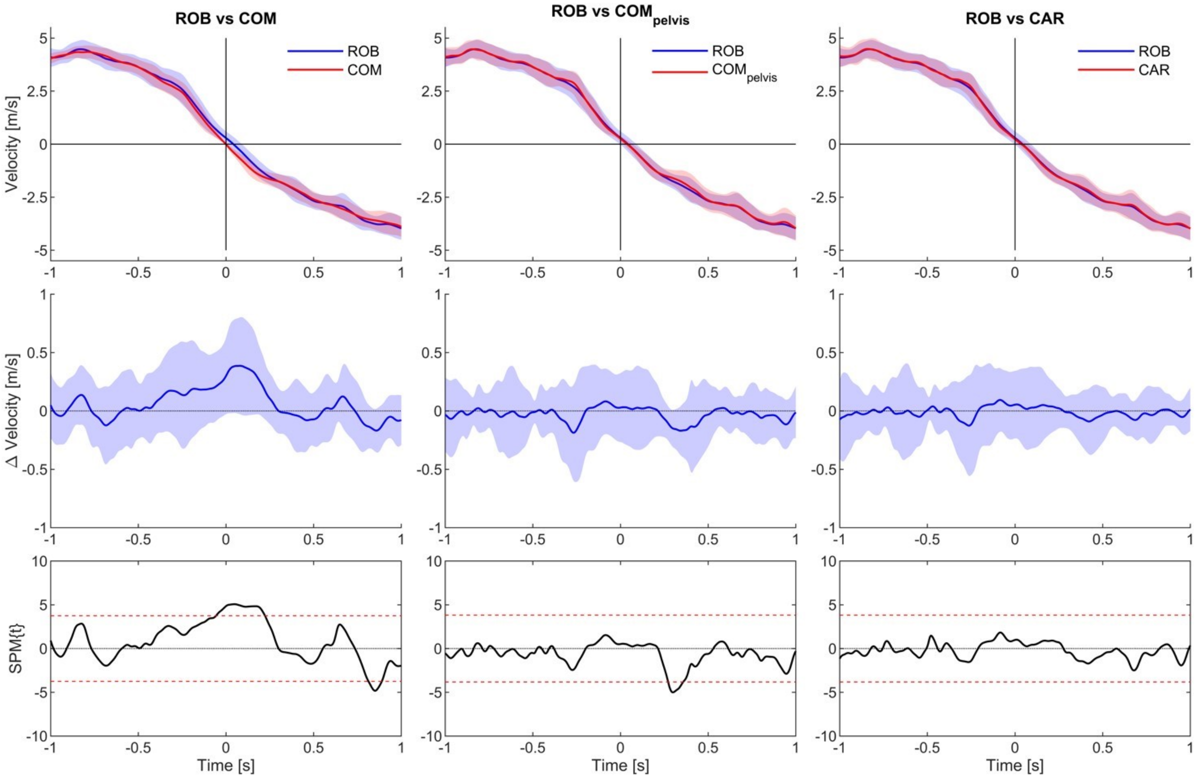
ROB vs COM
ROB vs COM$_{pelvis}$
ROB vs CAR
ROB
COM
COM$_{pelvis}$
CAR
Velocity [m/s]
Δ Velocity [m/s]
SPM{t}
Time [s]
5
2.5
0
-2.5
-5
1
0.5
-0.5
-1
10
-10
-1
-0.5
0
0.5
1

Figure 6

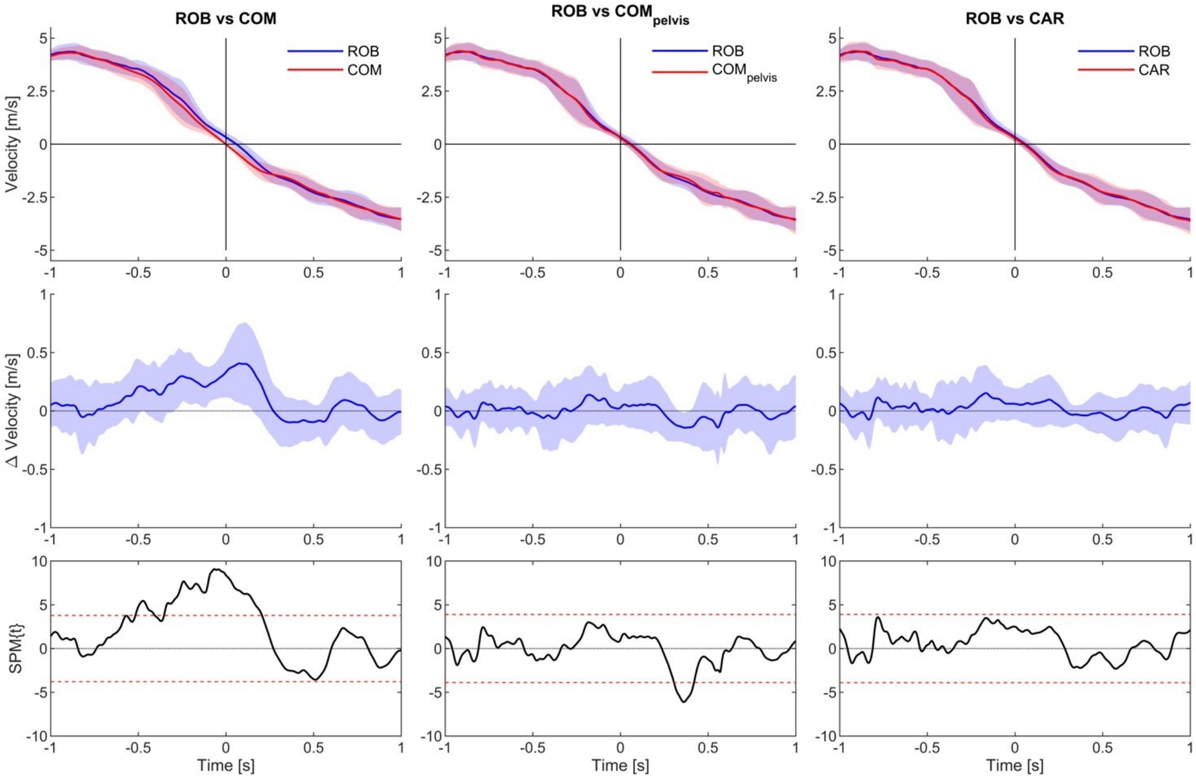

Table 1. m505 test results for the different loaded conditions

Performance variable	**3 kg**		**6 kg**		**9 kg**	
	M	SD	M	SD	M	SD
m505$_{time}$ (s)	3.26	.29	3.32	.35	3.52	.33
m505$_{dist}$ (m)	9.71	.33	9.81	.42	10.02	.45
m505$_{1a\_time}$ (s)	1.78	.15	1.77	.22	1.83	.15
m505$_{1a\_dist}$ (m)	4.86	.16	4.91	.21	5.01	.23
m505$_{1a\_avgvel}$ (m/s)	2.76	.17	2.83	.22	2.78	.16
m505$_{1b\_time}$ (s)	1.47	.16	1.56	.16	1.69	.21
m505$_{1b\_dist}$ (m)	4.86	.16	4.91	.21	5.01	.23
m505$_{1b\_avgvel}$ (m/s)	3.24	.27	3.10	.25	2.94	.27

M, mean; SD, standard deviation; m505$_{time}$, total time; m505$_{dist}$, total distance; m505$_{1a\_time}$, time phase 1a; m505$_{1a\_dist}$, distance 1a; m505$_{1a\_avgvel}$, average velocity phase 1a; m505$_{1b\_time}$, time phase 1b; m505$_{1b\_dist}$, distance 1b; m505$_{1b\_avgvel}$, average velocity phase

Table 2. Construct validity of robotic resistance device

Load (kg)	**Interval**	**ROB$_{vel}$**		**CAR$_{vel}$**						**COM$_{pelvis\_vel}$**											
		M	SD	M	SD	Bias (CI LOA)	Correlation	CV	n/n_{tot}	M	SD	Bias (CI LOA)	Correlation	CV	n/n_{tot}	M	SD	Bias (CI LOA)	Correlation	CV	n/n_{tot}
3	-1.0 to -1.5	3.39	.26	3.36	.25	-.023 (-0.55; .010)	r=1.00	.5 (.4; .7)	24/40	3.52	.24	.128 (.006; .25)	r=.97	1.7 (1.3; 2.3)	23/40	3.45	.23	.072 (-.073; .22)	r=.96	1.9 (1.5; 2.6)	23/40
	-0.5 to -1.0	4.03	.24	4.02	.23	-.012 (-.04; .02)	r=1.00	.4 (.3; .4)	40/40	3.96	.27	-.064 (-.18; .050)	r=.98	1.4 (1.2; 1.8)	39/40	3.94	.27	-.090 (-.22; .038)	r=.98	1.5 (1.3; 1.9)	39/40
	0 to -0.5	1.92	.35	1.95	.36	.026 (-.023; .076)	r=1.00	1.3 (1.1; 1.7)	40/40	1.69	.33	-.23 (-.33; .13)	r=.99	2.9 (2.4; 3.5)	39/40	1.50	.33	-.435 (-.64; -.23)	r=.96	7.4 (6.2; 9.3)	39/40
	0 to 0.5	-1.77	.26	-1.73	.26	.039 (.036; .11)	r=.99	2.3 (2.0; 2.9)	40/40	-1.89	.28	-.126 (-.25; 8.43)	r=.97	3.7 (3.1; 4.6)	39/40	-2.03	.26	-.259 (-.44; -.074)	r=.93	5.1 (4.3; 6.3)	39/40
	0.5 to 1.0	-3.68	.38	-3.65	.38	.032 (.0027; .061)	ρ=1.00	.4 (.3; .5)	40/40	-3.78	.39	-.094 (-.19; .005)	r=.99	1.4 (1.2; 1.8)	39/40	-3.77	.40	-.079 (-.19; .03)	ρ=.98	1.6 (1.3; 1.9)	39/40
	1.0 to 1.5	-3.95	.43	-3.95	.40	-.004 (-.072; .064)	r=1.00	.7 (.5; 1.2)	9/40	-3.88	.45	.042 (-.13; .22)	r=.98	2.6 (1.8; 5.0)	8/40	-3.83	.44	.082 (-.055; .22)	r=.99	2.1 (1.4; 4.0)	8/40
6	-1.0 to -1.5	3.53	.22	3.50	.22	-.029 (-.048; -.01)	ρ=.99	.3 (.2; .4)	18/40	3.62	.20	.097 (.002; .191)	r=.98	1.0 (0.8; 1.5)	17/40	3.55	.18	.022 (-.139; .183)	r=.93	1.9 (1.5; 2.8)	18/40
	-0.5 to -1.0	4.03	.29	4.02	.28	-.016 (-.036; .005)	r=1.00	.2 (.2; .3)	38/40	3.98	.30	-.065 (-.143; .040)	r=.99	1.0 (0.8; 1.2)	36/40	3.96	.31	-.075 (-.207; .058)	r=.98	1.7 (1.4; 2.1)	38/40
	0 to -0.5	1.92	.27	1.94	.29	.017 (-.019; .053)	r=1.00	.8 (.7; 1.0)	39/40	1.68	.25	-.241 (-.321; -.161)	r=.99	2.3 (1.9; 2.9)	36/40	1.46	.29	-.461 (-.627; -.295)	r=.96	6.5 (5.5; 8.2)	39/40
	0 to 0.5	-1.65	.24	-1.62	.24	.037 (-.022; .095)	r=1.00	2.0 (1.7; 2.5)	39/40	-1.77	.26	-.120 (-.225; -.014)	r=.98	3.0 (2.5; 3.8)	36/40	-1.91	.26	-.252 (-.406; -.098)	r=.96	4.3 (3.6; 5.3)	39/40
	0.5 to 1.0	-3.41	.42	-3.38	.42	.034 (.004; .064)	ρ=1.00	.5 (.4; 0.6)	39/40	-3.48	.43	-.075 (-.154; .004)	ρ=.98	1.2 (1.0; 1.6)	36/40	-3.47	.42	-.062 (-.147; .023)	ρ=.98	1.3 (1.1; 1.6)	39/40
	1.0 to 1.5	-3.88	.19	-3.87	.19	.005 (-.054; .064)	r=.99	.8 (.6; 1.2)	13/40	-3.87	.25	-.005 (-.170; .159)	ρ=.89	2.1 (1.5; 3.3)	12/40	-3.82	.22	.061 (-.156; .277)	ρ=.53	3.0 (2.2; 4.7)	13/40
9	-1.0 to -1.5	3.75	.24	3.72	.24	-.027 (-.050; -.003)	r=1.00	.3 (.3; .4)	29/44	3.82	.22	.077 (-.032; .186)	r=.98	1.2 (1.0; 1.5)	28/44	3.77	.22	.015 (-.146; .177)	r=.94	2.0 (1.6; 2.5)	29/44
	-0.5 to -1.0	3.91	.32	3.90	.32	-.012 (-.033; .009)	r=1.00	.3 (.2; .3)	44/44	3.83	.33	-.081 (-.150; -.012)	r=1.00	.8 (.7; 1.0)	42/44	3.79	.38	-.118 (-.284; .047)	r=.98	2.0 (1.7; 2.4)	44/44
	0 to -0.5	1.61	.34	1.61	.35	-.001 (-.050; .048)	r=1.00	1.8 (1.5; 2.2)	44/44	1.36	.32	-.246 (-.341; -.150)	r=.99	3.5 (2.9; 4.3)	42/44	1.12	.33	-.486 (-.650; -.322)	r=.97	7.7 (6.5; 9.5)	44/44
	0 to 0.5	-1.51	.28	-1.46	.29	.050 (-.031; .131)	r=.99	3.2 (2.7; 3.9)	44/44	-1.59	.33	-.090 (-.227; .047)	r=.98	4.3 (3.6; 5.3)	42/44	-1.68	.34	-.170 (-.358; .019)	r=.97	4.9 (4.1; 6.0)	44/44
	0.5 to 1.0	-3.08	.43	-3.05	.43	.022 (-.030; .075)	r=1.00	.9 (.8; 1.1)	43/44	-3.15	.43	-.089 (-.183; .004)	r=.99	1.6 (1.3; 1.9)	41/44	-3.15	.43	-.075 (-.166; .017)	r=.99	1.5 (1.3; 1.9)	43/44
	1.0 to 1.5	-3.63	.22	-3.62	.21	.009 (-.033; .051)	r=1.00	.6 (.5; .8)	22/44	-3.65	.22	-.031 (-.148; .085)	r=.96	1.7 (1.4; 2.4)	21/44	-3.62	.23	.017 (-.146; .179)	r=.93	2.4 (1.9; 3.3)	22/44