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The Force Platform Project

How to Compare Jump Height Measured by Different Force Platform Systems?

Master thesis in Sport Sciences
Department of Physical Performance
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Abstract

Background: Maximal vertical jump height is one of the most frequently reported generic performance variables, both in the scientific literature and when testing athletes. Jump height may be measured in different ways, but the force platform is the most popular method, as it is the only technology that measures the kinetic aspect of a jump. Agreements between force plate systems are important if jump height is to be used as a generic neuromuscular lower body test because various force platform systems are used at different testing facilities. To date, limited information exists regarding the agreement between different commercial hardware and software providers. **Purpose:** To compare jump height measured by four portable force platform systems. **Methods:** The portable force platform systems Kistler, ForceDecks, MuscleLab, and HurLabs, were placed on top of an in-ground reference force platform (AMTI) to measure the ground reaction forces (GRFs) concurrently during a jump. Squat jumps, countermovement jumps, and drop jumps were analyzed. 3D motion capture was collected simultaneously. The raw force data obtained from both force platform systems concurrently were extracted and analyzed through the same algorithm (set as reference calculation; Hardware). Moreover, the GRFs measured from the portable force platforms were calculated with the reference calculation and their software calculation to obtain jump height (Software). **Results:** For all jump modalities, the systematic difference in jump height between the portable systems and the reference system ranged from −2.9% to 3.8% for the Hardware analysis, and from −11.6% to 11.1% for the Software analysis. The typical error of estimate (%) ranged from 1.1% to 5.0% for the Hardware analysis, and from 3.2% to 22.3% for the Software analysis. For all jump modalities and analyses, all force platform systems differed significantly from each other ($p \leq 0.05$). **Conclusions:** Even when applying identical jump protocols and calculation procedures, there were differences in jump height measured by different force platform systems. Different force platforms should be used interchangeably in this way with caution. Software calculations should not be expected to be accurate, and different software cannot be used interchangeably for jump height measures if accuracy of less than 2 ± 2 cm is important. The results of this thesis are useful to understand and interpret jump height measured from different commercial force platform suppliers.

Sammendrag (abstract in Norwegian)

Bakgrunn: Spensthopptester er mye brukt for å måle «eksplosive» egenskaper hos idrettsutøvere, der den maksimale vertikale hopphøyden er den hyppigste rapporterte variabelen fra spensttester, både i forskning og i praksis. En kraftplattform anses som det beste instrumentet for spensttester, og er økende brukt i praksisfeltet. Utøvere testes ofte på ulike kraftplattformsystemer, og resultater fra forskningen sammenliknes også på tvers av utstyr. Per dags dato har vi lite kunnskap om enigheten i hopphøyde målt fra ulike kommersielle kraftplattformsystemer, slik at vi må sammenlikne resultater fra ulike systemer med stor forsiktighet. **Formål:** Å sammenlikne hopphøyde målt fra fire bærbare kraftplattformsystemer. **Metode:** De bærbare kraftplattformsystemene Kistler, ForceDecks, MuscleLab og HurLabs ble plassert oppå en gulvmontert referanse kraftplattform (AMTI) for å måle reaksjonskreftene fra bakken samtidig under et hopp. Knebøyhopp, svikthopp og fallhopp ble analysert. 3D-kinematiske analyser av vertikal forflytning av massesenteret ble målt samtidig. Rådataen ekstrahert samtidig fra begge kraftplattformsystemer ble analysert i samme algoritme (satt som referanse utregning; Maskinvare). I tillegg ble kraftmålingene fra de bærbare kraftplattformene kalkulert med referanseutregningen og den proprietære programvareutregningen for å oppnå hopphøyde (Programvare). **Resultater:** For alle hoppmodaliteter var den systematiske forskjellen mellom de bærbare systemene og referansesystemet mellom −2,9 % og 3,8 % for Maskinvare-analysen, og mellom −11,6 % og 11,1 % for Programvare-analysen. Tilfeldige feil *(«typical error of estimate»* (%)) var mellom 1,1 % og 5,0 % for Maskinvare-analysen, og mellom 3,2 % og 22,3 % for Programvare-analysen. For alle hoppmodaliteter og analyser, skilte alle bærbare kraftplattformsystemer seg signifikant fra hverandre ($p \leq 0,05$). **Konklusjon:** Selv når identiske hopp-protokoller og kalkuleringsmetoder ble anvendt så var det forskjeller i hopphøyde målt fra ulike kraftplattformsystemer. Det må derfor vises varsomhet når forskjellige kraftplattformsystemer brukes om hverandre på denne måten. Programvareutregningene bør ikke forventes å være nøyaktige, og kan ikke brukes om hverandre om en nøyaktighet på under 2 ± 2 cm er viktig når hopphøyde testes. Resultatene fra dette prosjektet er nyttige for å bedre kunne forstå og tolke hopphøyde målt fra ulike kommersielle kraftplattformsystemer.

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Project Information

This thesis is part of a project dedicated to the accuracy of the force platform system for jump assessments. The idea originated from the Norwegian Olympic Center. The experimental approach has been constructed in the project group which is outlined below.

Supervisors

Gøran Paulsen (main supervisor): Professor at the Department of Physical Performance, Norwegian School of Sport Science.

Øyvind Gløersen (second supervisor): Researcher at SINTEF.

Project group

Paul Solberg: Head of the strength and power division at the Norwegian Olympic and Paralympic Committee and Confederation of Sports.

Gertjan Ettema: Professor at the Norwegian University of Science and Technology.

Steinar Bråten: Researcher at the Norwegian University of Science and Technology.

Olivier Seynnes: Professor at the Department of Physical Performance, Norwegian School of Sport Science.

Amelie Werkhausen: Post Doc at the Department of Physical Performance, Norwegian School of Sport Science.

Hannah Rice: Associate professor at the Department of Physical Performance, Norwegian School of Sport Science.

Their contribution to this thesis is outlined in *Attestation of Authorship*.

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge, it does not contain material that has previously been published, collected, analyzed, or written by another person.

Part III is outlined as an article draft, which has not been submitted for publication. My contribution to this work and that of the co-authors are outlined below.

Conceptualization and Methodology: Gøran Paulsen, Øyvind Gløersen, Paul Solberg, Olivier Seynnes, Gertjan Ettema, Steinar Bråten, Ingrid Eythorsdottir. **Data collection:** Ingrid Eythorsdottir, Øyvind Gløersen. **Data analysis:** Ingrid Eythorsdottir, Øyvind Gløersen, Gøran Paulsen, Hannah Rice, Amelie Werkhausen. **Statistical Analysis:** Ingrid Eythorsdottir, Gøran Paulsen, Øyvind Gløersen, Paul Solberg, Amelie Werkhausen. **Data visualization:** Ingrid Eythorsdottir, Øyvind Gløersen, Gøran Paulsen, Amelie Werkhausen. **Writing - article draft:** Ingrid Eythorsdottir. **Writing—reviewing and editing:** Gøran Paulsen, Øyvind Gløersen.

I declare that I have to the best of my ability collected, analyzed, and visualized the data myself, although each of the persons listed in these paragraphs above have participated in this process as needed. All main calculation scripts were written in collaboration with Øyvind Gløersen.

Ingrid Eythorsdottir

Oslo, 01.06.2022

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Although my name stands alone on the front page of this thesis, this endeavor would not have been possible without the guidance and support of many.

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To both, thank you for always having your doors open. Your kindness and patience were very much appreciated. You have motivated me, challenged me, guided me, and believed in me. The completion of this thesis would literally not have been possible without your support. You are my superheroes and biggest inspiration!

My sincerest thanks go also to the project group, which I am privileged to have worked with: **Paul Solberg,** for reminding me of the importance of this project, setting up contacts, and giving statistical guidance. **Olivier Seynnes,** for always having your door open, and being willing to discuss whatever I bring up. **Amelie Werkhausen,** for your positive attitude and help with figure making, plus more (!). **Hannah Rice,** for jumping into the project, answering all my questions, and patiently helping with the analyses. **Gertjan Ettema and Steinar Bråten,** for sharing your expertise and experience with force platform testing and its technology.

Thank you to the **guys at Olympiatoppen** for patiently lending us your equipment. Thanks to **Ola (NIH)** and **Katie (Visual 3D)** for valuable help on the kinematic model building. Thanks to **Ole** (MuscleLab), **Nick and Nicci** (Vald performance), and **Anssi** (HurLabs) for the discussions and for answering my questions. Thank you to **all the participants** who jumped into my master thesis!

At last, I could not have undertaken this journey without **my friends and family** who have supported me, believed in me, and cheered me on—Thank you! Especially, **Mamma, Pappa, Olav, Eirik, Ida**, and of course our family dog **Baldur**. You guys are the best!

Tusen takk til dere alle og takk for meg! ☺

Ingrid Eythorsdottir
Oslo, June 2022

List of Common Abbreviations

a: *acceleration*

CL: *confidence limits*

cm: *centimeter*

CMJ: *countermovement jump*

CoM: *center of mass*

diff: *difference*

DJ: *drop jump*

F: *force*

g: *gravitational acceleration*

GRF: *ground reaction force*

Hz: *hertz*

kg: *kilogram*

m: *mass*

max: *maximum*

min: *minimum*

mm: *millimeter*

N: *newton*

n: *number*

p: *probability value*

SD: *standard deviation*

s: *second*

SJ: *squat jump*

TEE: *typical error of estimate*

V: *voltage*

3D: *three-dimensional*

%: *percentage*

>: *more than…*

<: *less than…*

$\int$: *integral*

Part I – Introduction

Background

Maximal vertical jump height is the most frequently used generic test for neuromuscular performance of the lower extremities, both in the sports science literature and for assessing athletes (Jiménez-Reyes et al., 2014; Haugen et al., 2018; Morin et al., 2019; Cross et al., 2021; Lindberg et al., 2022). The height we elevate our body off the ground indicates our ability to oppose gravity, which rationalizes the maximal vertical jump as one of the most popular tests for general motor ability and movement performance (Sargent, 1921; Bobbert et al., 1986; Oddsson, 1987; Aragón-Vargas, 2000; Cronin et al., 2004; Cormack et al., 2008; Jiménez-Reyes et al., 2017; Montalvo et al., 2021).

By laws of Newtonian physics, a vertical jump is determined by the elevation of the center of mass (CoM). Accordingly, jump height can be measured by tracking the displacement of the CoM through a jump (Marey & Demenÿ, 1885; Dias et al., 2011; Rago et al., 2018; Montalvo et al., 2021).

To date, three-dimensional (3D) motion capture systems provide the most direct measure of CoM positions and movements (Dias et al., 2011; Rago et al., 2018; Montalvo et al., 2021). However, the equipment needed for these measures poses significant environmental constraints, especially for in-field testing of athletes (van der Kruk & Reijne, 2018; Nakano et al., 2020). For these reasons, indirect methods to calculate jump height have been developed, such as force platforms (Street et al., 2001; McMahon et al., 2018), contact mats (Bosco et al., 1983), photoelectric cells (Glatthorn et al., 2011), and smartphone (video/accelerometer) applications (Balsalobre-Fernández et al., 2015). Of all the available technologies and methods, the force platform is arguably the device that could give the most valuable information obtained from a vertical jump. The force platform is the only technology that allows a comprehensive analysis of the kinetic aspect of a jump, i.e., the forces involved in producing the jump (Beckham et al., 2014; McMahon et al., 2018).

A force plate is in its simplest form a device that records the ground reaction forces during a vertical jump (Figure 1), which from movement strategies and performance variables such as jump height can be calculated (Linthorne, 2001; Beckham et al., 2014; McMahon et al., 2018).

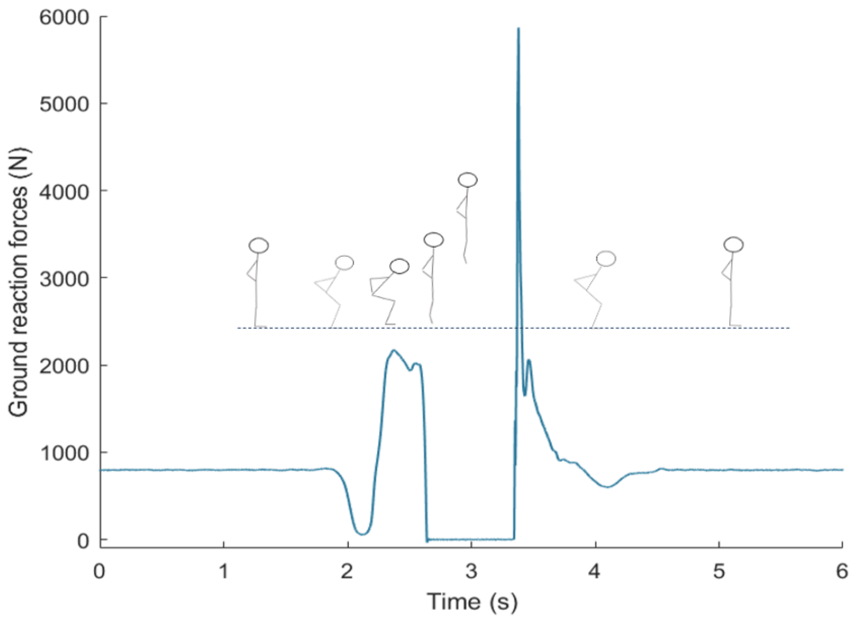

Figure 1. *The ground reaction forces (N) measured by a force platform (not depicted) are plotted as the blue solid line against time (s), during a countermovement jump. The stick figures represent a person performing a countermovement jump on the ground (depicted as the blue dotted line). Own illustration made in MATLAB (R2021b version; Math-Works, Inc, Natick, MA) and Microsoft® PowerPoint, v. 16.54 (Microsoft 365, Microsoft Corporation).*

Three types of vertical jump tests are commonly used: the squat jump (SJ), the countermovement jump (CMJ), and the drop jump (DJ). As the SJ starts from a static squat position (typically held for 1–2 s), SJ assesses concentric force development; whereas CMJ and DJ utilize the ability to pre-load the muscle-tendon system with a countermovement prior to the concentric contraction (i.e., an eccentric-concentric contraction, also called a plyometric contraction) (Bobbert et al., 1986; Bobbert & Casius, 2005; Addie et al., 2019). Indeed, these three jump modalities require different strategies, which are mirrored in distinct GRF-time curves obtained from a force platform (Asmussen & Bonde-Pedersen, 1974; Bosco & Komi, 1979; Lees & Fahmi, 1994).

Traditionally, force platform systems were merely found in laboratories, as they were expensive and required specific setups relying on expertise skills (both hardware- and software wise) (Seiberl et al., 2018). However, today, force platform systems are increasingly accessible for testing athletes in field settings, as they exist in portable and more affordable forms, including a software that produces instant results. In fact, these trends are easily mirrored in the literature. Over the last five years, an increasing number of research related to the implementation of the force platform for jump assessments in field settings, and to guide practitioners on how to use the force platform most effectively, have been published (Barker et al., 2018; Chavda et al., 2018; Lake & McMahon, 2018; McMahon et al., 2018; García-Ramos et al., 2020; Harry et al., 2020; Philpott et al., 2020; Bishop et al., 2021; Harry, 2021; Kennedy & Drake, 2021; McMahon et al., 2021; Wilder et al., 2021; McMahon et al., 2022; McMahon et al., 2022).

The value of the force platform is, however, entirely dependent on how accurately the force platform system measures the ground reaction forces and from there, e.g., calculates jump height (Street et al., 2001). The agreement between different force plate systems is especially relevant as athletes are usually tested at different test facilities/centers with different force platform systems (Lindberg et al., 2022). Similarly, in research, results are often compared across research facilities using different test equipment, e.g., in meta-analyses (de Villarreal et al., 2009), or multicenter studies (García-Ramos et al., 2020; Lindberg et al., 2022). The fact that jump testing was performed on different systems, indicates how jump height was analyzed slightly differently, making it challenging to compare results measured at different research/test facilities.

From years of experience with jump testing at the Norwegian Olympic Center (Haugen et al., 2021; Lindberg et al., 2022), there have been observed substantial discrepancies in jump height measured by different force platform systems in athletes with highly stable jump heights (e.g., ski-jumpers)—leading us to question the comparability of jump height measured by different force platform systems (personal communication with Paul Solberg and Gøran Paulsen, Strength and Power division at the Norwegian Olympic Center). The anecdotal observations from the field (Norwegian Olympic Center) are scarcely investigated in scientific studies. To date, only a single study has investigated the concurrent validity of a portable force platform against an in-ground laboratory force platform for jump height outcomes (Lake et al., 2018), which is surprising considering the number of commercially available force platform systems available for jump assessments.

By investigating the agreement between different hardware and software providers, larger data sets can be collected, which will strengthen the value of jump testing for both researchers and practitioners/athletes.

Thesis aims

The aim of this thesis was to compare jump height measured by four different force platform systems and to examine whether differences in jump height could be attributed to the systems' hardware or software. Jump height was measured from the SJ, CMJ, and DJ.

The thesis experimentally tested the following hypotheses:

i) There are significant differences in jump height measured by different force platform systems.

ii) These differences are primarily attributed to the different software (different algorithms used to calculate jump height) and to a lesser extent hardware differences.

Thesis structure

This thesis is structured in two parts from here.

In **Part II** the theoretical and methodological approach to this thesis is outlined. It comprises a series of six sub-sections highlighting various topics which have laid the foundation of this project.

Part III is written in form of an article, dedicated to the aims and hypothesis addressed above. Some of the information in **Part III** will overlap with the information given in this part and that in **Part II**. Please note that abbreviations, equations, and figure numbers are written independently from those given in **Parts I & II**.

PART II – Theory & Methodology

Preface

In this second part, the theoretical and methodological background of this thesis will be outlined. *Section 1* offers a brief view of the history of the force platform. *Section 2* is dedicated to the importance of accurate measurements. *Section 3* will outline some basic principles regarding the technology of the force platform. *Section 4* will outline the basic principles needed to calculate jump height from force plate recordings. *Section 5* is concerned with center of mass modeling as an alternative for measuring jump height. *Section 6* offers a general overview of the experimental approach for the remainder of this thesis. In *section 6* there will be some overlap with the experimental approach as written in **Part III**.

To support the use of some technical terms, an appendix follows which describes the nomenclature and definition of terms that will be outlined in this part—and throughout this thesis (*Appendix I*). The more important technical terms will be explained throughout this part.

Section 1 – A brief history

"Jumping is cleverly dealt with by Nature and must be considered" (Borelli, 1680/1989, pp. 155). Our interest in such a seemingly simple movement as jumping serves a long origin. By taking a step back in time to see what originally fascinated us with jumping, it becomes quite clear why the force platform is such a popular technology for jump assessments. In this section, a brief view of the history of understanding how we are able to jump, and how these observations resulted in the force platform, will be given.

1.1 Gravity, force, and jumping – how are they related?

"There is, in nature perhaps nothing older than motion..." (Galilei, 1632/1914, pp. 153). Galileo Galilei was interested in many things, such as the movement of a body in motion. It was especially his interest in the motion of a naturally accelerated body, opposing gravity, that led him to begin the journey of understanding what enables us to jump.

Galilei demonstrated how, for a body to project upwards (i.e., oppose gravity), a *force* was needed. However, this force would only impel the body upwards if it was greater than the contrary force of *gravity*. At one point, the force used to project a body upwards and the force of gravity would reach an equilibrium. At this point, the body would cease to rise and pass through a state of rest. Then, as gravitation gained the upper hand, the fall would begin (Galilei, 1632/1914, pp. 165). These descriptions are essentially a description of a jump.

Giovanni Alfonso Borelli was a student of Galilei's former student, Benedetto Castelli, and Borelli's work built on many of Galilei's previous discoveries (Pope, 2005, pp. 2350). In Borelli's work *De Motu Animalium (On the Movement of Animals)* published between 1680 and 1681, lies, what is to the author's knowledge, the very first descriptions regarding jump mechanisms in humans—further supporting Galilei's observations.

Borelli (1680/1989) explained why a jump is impossible without flexion of the legs. He stated that as long as a man stands upright, whatever he would generate of will and effort, he couldn't jump. If flexing the joints of the legs though, energetic contractions of the extensor muscles could result in a jump. Yet, simply bending and extending the legs would not necessarily result in a jump. For the jump to be obvious, extensions of the joints, made by the glutei, vasti, and triceps surae muscles, must be considerable in magnitude and quickness. More specifically, Borelli demonstrated how the CoM lowered as the legs bent, creating a resistance to the ground, and *by reaction*, this resistance would further raise the CoM as the legs extended—resulting in a jump (pp. 155–161).

Galilei's and Borelli's work perspicuously explained how jumping is related to a force, a reaction force, and gravity. Nonetheless, there was not a way of quantifying these relationships and how they affected each other—that is, the exact relations between force, gravity, and jumping remained unknown until Sir. Isaac Newton published his three, now universal, laws of motion (Newton, 1712/2021, pp. 45–46):

Law I: "Every body preserves either in its state of resting or of moving uniformly in a direction, unless that is compelled to change its state by impressed forces".

Law II: “The change of motion is proportional to the magnitude of the impressed motive force, and to be made along the right line by which that force is impressed”.

Law III: “To an action there is always an equal and contrary reaction: or the actions of two bodies between themselves are always mutually equal and directed in opposite directions”.

Especially Newton’s second law, which the reader might be more familiar with as $\sum F = m \cdot a$, where $\sum F$ = the sum of all forces measured in newtons, m = mass of the body, a = acceleration, and Newton’s third law, is the direct reason why a force platform exists and is used to assess movements that oppose gravity—such as jumping (Beckham et al., 2014).

As is common knowledge today, the natural forces of gravity work by pulling us towards the ground. The only way for us to oppose gravity and jump is to apply a force to the ground, as described by Galilei and Borelli. More specifically, Newton’s second law of motion states how, assuming a constant mass, an increase in net force will increase acceleration. Continuing on the path of physics, a positive acceleration will increase velocity, which in turn will increase the displacement of the CoM, or in other words, jump height. The reader is directed to *section 4* for more detailed and accurate descriptions of these relationships.

According to Newton’s third law of motion, when a force is applied, in this case to the ground, the ground responds with a force equal in magnitude but opposite in direction. This respondent force is better known as the ground reaction force (GRF) (Beckham et al., 2014, pp. 26). Thus, if one could measure the GRFs, pertinent observations with regard to jumping could be made.

A force platform is in its simplest form a device that records Newton’s third law, i.e., the GRFs, and it is used for this purpose to assess a myriad of movements from jumping, walking, running, landing, pitching, kicking, etc. (Chen et al., 2021; McFadden et al., 2022; Taniguchi et al., 2022; Thompson et al., 2022; van den Bogaart et al., 2022). But how does a force platform work, and how was the technology developed?

1.2 The first force platform

The journey of the force platform began in Paris at the *'Academie des Sciences, Institut de France'* where a researcher by the name of Étienne-Jules Marey worked. Marey is known for further improving the developments made by Mr. Muybridge who revolutionized the use of video as a tool for motion analyses in the 1870s (Chiari et al., 2005, pp. 198). Indeed, Marey himself conducted several movement analyses using video but recognized a limitation to this approach; it could only give information related to the kinematic aspect of a movement, e.g., distance and speed. What still needed to be known were the *causes* of these movements (Marey, 1883, pp. 1). Hence, Marey, together with his colleagues Mr. Demenÿ (physiologist) and Mr. Lund (mechanist), set out to build, the very first force platform (Figure 2).

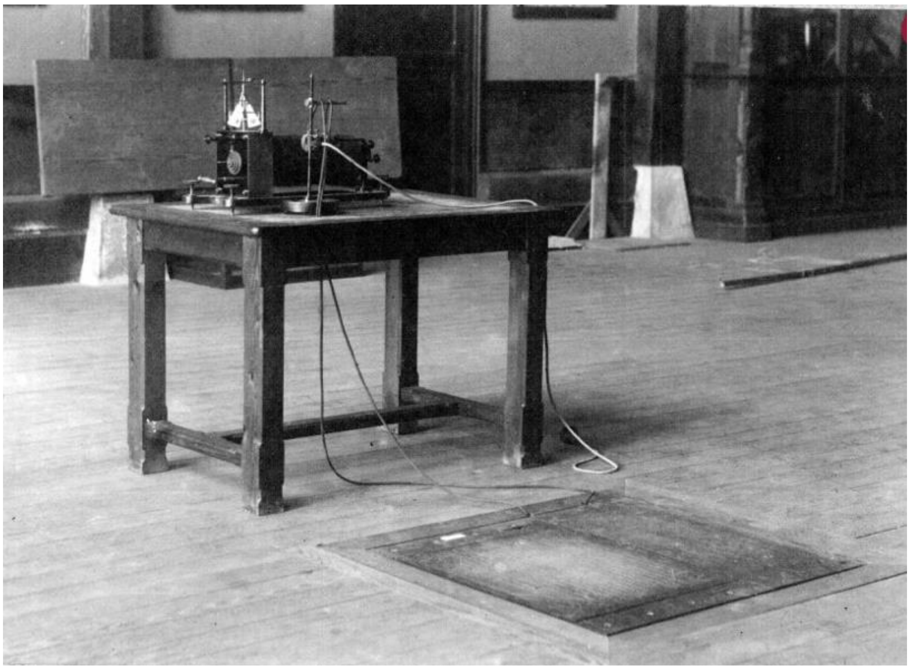

Figure 2. *A picture of the first force platform in Paris at the 'Academie des Sciences, Institut de France'. From "De la measure des forces dans les different actes de la locomotion" by Marey 1883, Academie des Sciences.*

Today's force platforms are built on either strain gauge or piezoelectric force transducer technology (see *section 3*). Piezoelectric elements were first introduced in 1880 (Curie & Curie, 1880), and it would not be until the 1950s that this technology was applied in force platform measurements (Lauru, 1954). As for the strain gauges, these were first developed in the 1930s (Keil, 2017).

The first force platform estimated force creatively using pneumatic resistance (i.e., air resistance). To test the accuracy and possibilities of the force platform, Marey and colleagues choose to analyze jumping, because it was a simpler movement (only in one dimension) compared with walking or running (movements in all three dimensions). Specifically, they tested the SJ, CMJ, and DJ (Figure 3; trace E (SJ), F (CMJ), H (DJ)) (Marey, 1883). Even though the exact GRF values were not quite accurate (due to the technology limitation for estimating force at this time), the shapes of the GRF-time curves were rather convincing, as can be seen in Figure 3.

Fig. 1.

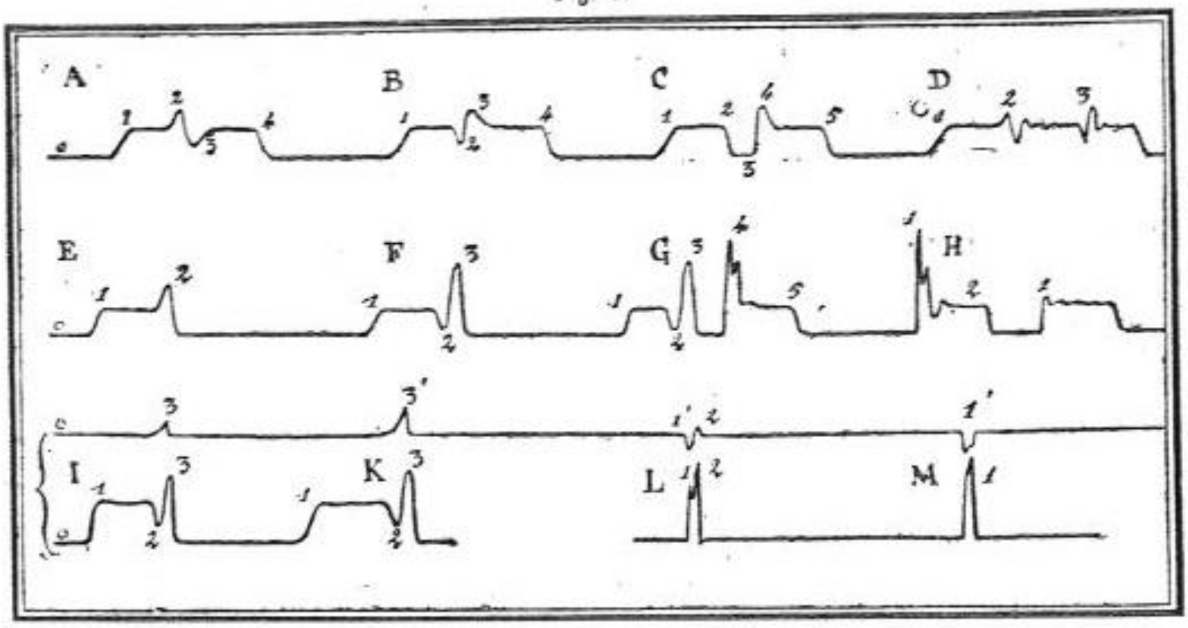

Figure 3. *A picture of the force platform tracings from the first experiment of the force platform. The top tracings represent experiments where the person bent and straightened his legs with various efforts (A, B, and C), or raised and lowered his arms (D). Curve E: A squat jump. Curve F: A countermovement jump. Curve G: A jump where the person landed on the heels. Curve H: A drop jump. The lower tracings represent the pressure exerted tangentially to the plane of the ground and the pressures applied perpendicular to this plan. Curve K & I: A long jump without a run-up. Curve L & M: A long jump with a run-up. From "De la measure des forces dans les different actes de la locomotion" by Marey, 1883, Academie des Sciences, pp. 5.*

Building on this work, in 1885, Marey and Demenÿ published the first experimental paper using the force platform to analyze jumping mechanisms in humans, concurrently with video. In this study, one individual performed two successive jumps; the first jump started from a squat position (SJ), and as such the second jump became a CMJ. Please see Figure 4 for the results of this experiment.

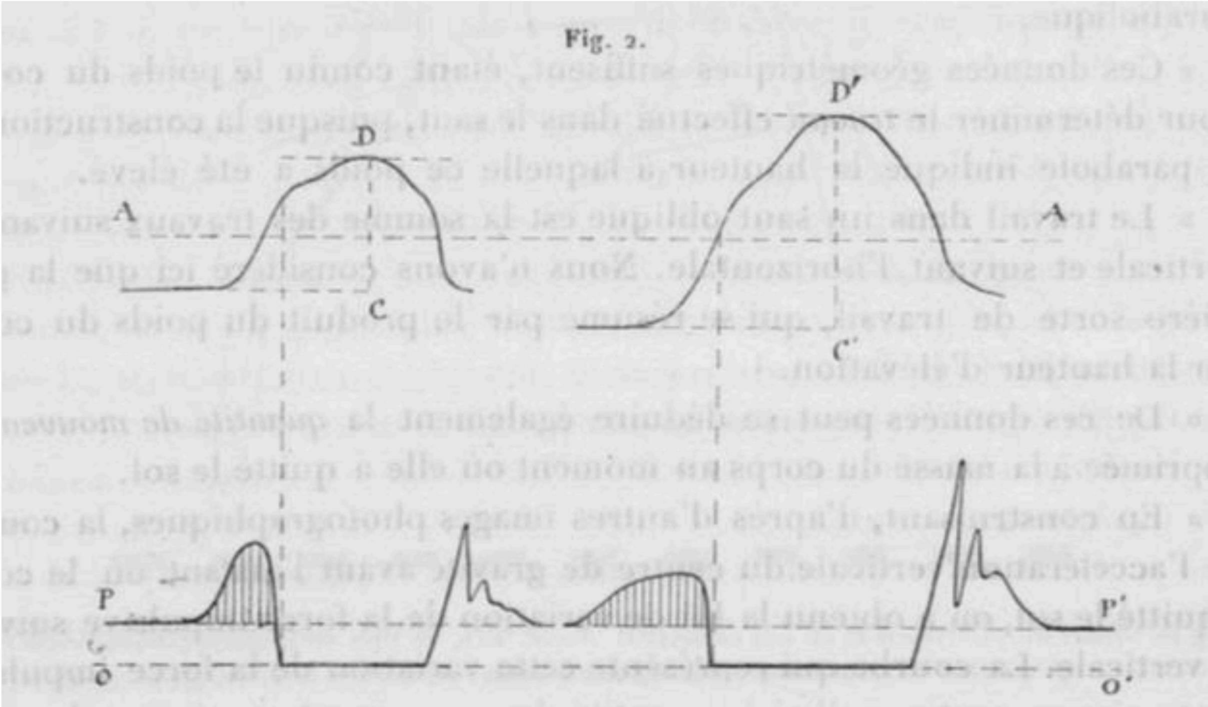

Figure 4. *A picture showing the results from the combined use of motion analysis (top tracings) and force platform recordings (bottom tracings) during two successive jumps. First jump= squat jump, second jump= countermovement jump. Top tracings: the path of the center of mass (CoM) obtained from video analysis. Bottom tracings: Ground reaction forces measured by the force platform during the jumps. The shaded areas in the bottom tracings represent the impulse (force over time). From "Locomotion humaine mechanism de saut" by Marey & Demenÿ, 1885, Academie des Sciences, pp. 4.*

The results from the two comprehensive and impressive papers addressed above rendered the authors to make several curious observations regarding jump mechanisms in humans. Concretely, from the GRF-time curves depicted in Figures 3 and 4, they observed and discussed how the same jump height could be reached with several different strategies. In other words, equal impulses (area under the GRF-time curve) could have numerous forms from the force platform tracings; an intense and short effort resulted in an equal force impulse as a less intense effort but of longer duration, and as such equivalent jump heights (Marey & Demenÿ, 1885, pp. 4–5). Moreover, they observed that the CMJ would be higher than the SJ, and from this speculated how the utilization of stored elastic energy, which would be enhanced by performing a preliminary countermovement in the CMJ, would increase the amount of force produced by the muscles. According to Newton's second law ($F = m \cdot a$), an increased force production would lead to greater acceleration in the CMJ, and hence superior jump heights (Marey, 1883; Marey & Demenÿ, 1885, pp. 6). Further, they speculated how using the arms when jumping would be linked to the same mechanisms, as well as if a jump was performed with a preliminary run-up (Marey & Demenÿ, 1885, pp. 6). These topics are still, as of today, given great attention (Bobbert et al., 1996; Linthorne & Weetman, 2012; Van Hooren & Zolotarjova, 2017; Haugen et al., 2018; Cross et al., 2021; Kozinc et al., 2021; Seiberl et al., 2021)—and the reader should note that all these discussions were brought to life based on the preliminary results from the force platform shown in Figures 3 and 4.

1.3 Where are we now?

Today, almost 140 years later, the force platform is considered the "gold standard" for force measurements during movements such as jumping. According to PubMed®, there are > 7700 research articles that have utilized the force platform, and there is a clear exponential increase in its use just over the very recent years (Figure 5).

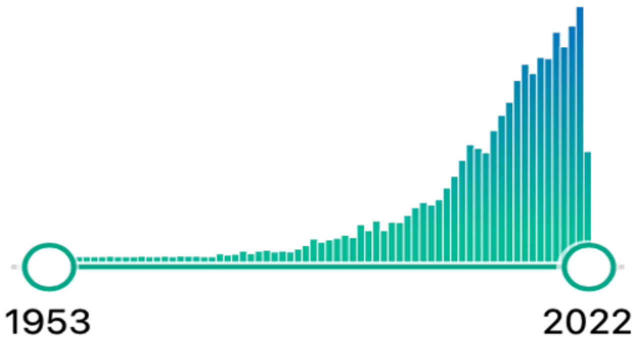

Figure 5. *A timeline depicting the number of publications using the force platform between the years 1953 and 2022. Own screenshot from the PubMed® webpage. The results are based on a search using «force plat*». There is a clear exponential increase in the use of the force platform over the recent years. Note that fewer publications in 2022 are mirroring that this search was conducted in May 2022.*

The "gold standard" status of the force platform simply stems from the fact that there are no direct alternatives to measure force during sports-related movements. It is, nevertheless, rather intriguing how a myriad of researchers state that the force platform is the "gold standard" for force measurements during human movements (García-López et al., 2013; Lesinski et al., 2016; Mengarelli et al., 2018; Richmond et al., 2018; Seiberl et al., 2018; Nielsen et al., 2019; Tenelsen et al., 2019; Barbalho et al., 2021; Menzel & Potthast, 2021; Królikowska et al., 2022; Patoz et al., 2022), and even for measuring maximal vertical jump height (Attia et al., 2017; Carlos-Vivas et al., 2018; Rago et al., 2018). The actuality is that these are only statements. The evidence to support the "gold standard" status of the force platform is sparse, especially when it comes to using the force platform to calculate performance variables such as jump height. Considering the popularity of the force platform, and how valuable it could be as a tool for movement analyses such as jumping, it is only fair to critically evaluate the accuracy of the force platform for jump assessments.

Section 2 – Testing accuracy

When testing, it is crucial that the measurement systems used are accurate. What accurate measurement systems imply will be described briefly in this section. The focus will be on the general principles used in this thesis, exemplified for jump testing on a force platform. Some common nomenclatures will be described, which are deemed important to understand the basis of this thesis. Of importance, for the purpose of this thesis, **accuracy** is defined as to what extent the test results (jump height) conform with the correct value, or a given standard. In this thesis, accuracy will entail both reliable and valid measures. Reliability and validity will be discussed separately elsewise. **Noise** is defined as unwanted irregularities in the signal, which are unrelated to the process being measured. **Error** is defined as an incorrect outcome value, which can be attributed to both noise, and e.g., method choices.

2.1 The value of testing

Performing a jump on a force platform is not a movement exactly mirroring any jumps performed in an athletic setting, such as jumping in volleyball or basketball, nor is jumping on a force platform an Olympic event. Even though jumping on a force platform is not entirely sport-specific, testing, in general, offers some great advantages regarding performance enhancement and for answering the research questions of interest.

In an athletic setting, test results are used to evaluate the effect of a training period or program (Lindberg et al., 2021), look at trends within a sport (Haugen et al., 2018; Haugen et al., 2021), and/or develop a performance capacity analysis (Hughes & Bartlett, 2002). Test results work like a map that helps steer the athlete and coaches in the right direction towards performance enhancement. That is, testing only works to guide athletes in the right direction if the test results are accurate.

In a research setting, test results are used to evaluate the effect of the given research. The test results are intended to advance our knowledge and understanding of the phenomenon we are interested in—and from there, wishfully change practice. Accurate tests are of crucial importance if ought to evaluate the effect of research with acceptable certainty (Atkinson & Nevill, 1998; Hopkins, 2000).

2.2 What affects the accuracy of any test results?

When testing, what is of interest is the *true* value—that is, the actual physiological/biomechanical characteristics of the person being tested, e.g., jump height. In reality, the actual test result (commonly known as the observed value) is the sum of the true value and error (Equation 2.1) (Bruton et al., 2000, pp. 95; Weir, 2005, pp. 232).

$$Test\ result\ =\ true\ value\ +\ error \qquad (2.1)$$

The theoretical true value can be viewed as the average of infinite tests within an individual, whilst the error is the difference between the true value and the test result (Weir, 2005, pp. 232).

As a purely theoretical value, test results will never truly mirror the true value. The accuracy of any test results is thus affected by what *degree* the test results are mirroring the true value—which depends on the magnitude of the error (Atkinson & Nevill, 1998; Bruton et al., 2000; Hopkins, 2000; Weir, 2005).

For example, pre- and post jump heights in an athlete are compared, following a given training intervention. The athlete jumped 43.2 cm pre-intervention. Post-intervention, the same athlete jumped 44 cm. Did the athlete improve jump height by 0.8 cm following the intervention? That depends entirely on the error associated with this test.

The jumps were measured on a force platform where one could expect an error in the magnitude of 1.2 cm. As the change in performance was smaller in magnitude than the expected error, we cannot conclude that the athlete did, in fact, improve jump height by 0.8 cm. It could simply be a measure of the error. However, if the jumps were measured on a force platform where one could expect an error in the magnitude of 0.2 cm, an improvement in jump height of 0.8 cm could be written as a true improvement in jump height (at least of 0.6 cm). Thus, the smaller the error in the measurement system, the easier it will be to detect an actual change in performance (Hopkins, 2000).

Especially when testing elite and high-performing athletes, where small improvements in performance are expected, the error associated with the performance test needs to be at a minimum (Lindberg et al., 2022). If the expected changes in performance are large, e.g., for untrained individuals performing a strength training intervention (Deschenes & Kraemer, 2002), one could arguably accept somewhat larger errors in the measurements, although clearly errors, in general, are not desirable.

2.3 Measurement error

The associated error with any testing could have several origins such as (Weir, 2005, pp. 232):

- Biological variation (individual biological differences between days/tests).
- Measurement instrument (the equipment and/or method used).
- Test person (e.g., motivation, learning effect, fatigue).
- Test leader (the person conducting the testing, e.g., instructions given).

The total error present in any measurements can be divided into two components: random errors and systematic errors (Atkinson & Nevill, 1998, pp. 220; Weir, 2005, pp. 232).

Random errors are random and hence unpredictable. The direction of the error (positive or negative) has no obvious pattern. The test equipment, e.g., a force platform, could yield some mechanical variations which could affect the magnitude of the random error (Atkinson & Nevill, 1998, pp. 220).

Systematic errors are systematic and hence predictable. The direction of the error (positive or negative) has a clear pattern. That is, there is a clear trend for the measurements to be different in a particular direction between tests (Bruton et al., 2000, pp. 95; Weir, 2005, pp. 232), where the differences show consistency with the size of the measurements (Olds, 2002, pp. 336). For example, the force platform could e.g., always overestimate jump height, or systematically underestimate jump height at higher jump heights (Atkinson & Nevill, 1998, pp. 220; Bruton et al., 2000, pp. 95).

The total error is the sum of random and systematic errors, and it is of utmost importance to quantify the magnitude of the overall error to the best extent to ensure accurate measurements (Atkinson & Nevill, 1998, pp. 220).

2.4 Methodological approaches

With proper study designs and statistical approaches, it is possible to quantify some of the errors, and thus, to what degree the test results are mirroring the true value (Atkinson & Nevill, 1998; Hopkins, 2000). Quantifying the measurement error allows one to decide whether a real change in performance has occurred, or whether the difference between measurements is solely due to errors (Olds, 2002, pp. 336). Such methodological studies are typically concerned with one of two points:

Reliability refers to the reproducibility of the measurements when they are repeated over time. **Validity** refers to what extent the measurement instrument is measuring what it is intended to measure (Atkinson & Nevill, 1998; Hopkins, 2000; Weir, 2005).

A test is only valid if it is reliable, and reliability should therefore be examined prior to validity when investigating the accuracy of any test (Thomas et al., 2015, pp. 208).

The reliability of jump assessments is well established. Most studies have reported within-session reliability with variations ranging from ~ 0.4% to 8.0% in jump height (CMJs, SJs, and DJs) when measured from a force platform, where larger variations have typically been observed in the SJ (Hatze, 1998; Hopkins, 2000; Cormack et al., 2008; Matheson et al., 2013; Thomas et al., 2017; Heishman et al., 2020; Merrigan et al., 2020). The between-session reliability in jump height has been reported to range from ~ 1% to 10% (Moir et al., 2009; Matheson et al., 2013; Thomas et al., 2017; Lindberg et al., 2021; Lindberg et al., 2022), where the largest variations were reported in multicenter studies wherein the test sessions were performed at different test centers (Lindberg et al., 2021; Lindberg et al., 2022). On average though, jump height as a performance variable is expected to have reasonable reliability, compared with strategy-related jump variables such as e.g., rate of force development, as the same jump height can be obtained with various strategies (Moir et al., 2009; McBride et al., 2010; Lindberg et al., 2022).

However, the reliability in jump height does not indicate valid measures, and research aimed at assessing the validity of jump height measured by different force platform systems is sparse.

Section 3 – Force platform technology

The accuracy of the force platform for calculating jump height could potentially be affected by several factors, but the overreaching factors are the hardware and software. For the purpose of this section, brief information regarding the function of the hardware components of the force platform, and how the hardware functions could potentially affect jump height outcomes, will be given. The software calculations will be addressed in the following section.

3.1 Force platform technology

A force platform is composed of a flat top, e.g., a rigid plate, supported by typically four force transducers, which give an electrical output proportional to the force applied to the plate (Cross, 1999, pp. 304; Browne & O'Hare, 2000, pp. 515; Silva et al., 2017, pp. 259). A force platform is either embedded in the ground (in laboratories) or provided as portable force platforms—where the former is commonly considered superiorly accurate when compared to the portable force platform systems (Walsh et al., 2006; Buckthorpe et al., 2012; Silveira et al., 2017; Lake et al., 2018). Regardless, their basic functions are similar. Force platforms operate on the principle that there is one resultant force vector, namely the GRF, which is numerically and physically equivalent to the sum of all the applied forces, regardless of the number of objects that apply forces to the plate, and the locations of these force applications (Robertson et al., 2014, pp. 94).

The process where force is converted into voltage (electric pressure) is called transduction, and a device that performs this function is called a transducer (Robertson et al., 2014, pp. 349). Current force platforms used for jump assessments are based on force transducers using strain gauge or piezoelectric technology (Ramey, 1975; Cross, 1999; Browne & O'Hare, 2000; Beckham et al., 2014).

3.2 Strain gauges

The strain gauge operates on the principle that when a force is applied to the force platform, the material of the force transducer deforms, called mechanical strain (Robertson et al., 2014, pp. 352). Specifically, when strained, the material of the strain gauge (a thin piece of metal foil), becomes thinner (with tensile strain) or thicker (with compressive strain), which in turn alters/reduces its ability to transmit electrical charge (Ramey, 1975, pp. 310; Robertson et al., 2014, pp. 92). The change in resistance is measured as a voltage signal by using a proper electrical circuit (typically the Wheatstone bridge) (Ramsey, 1975; Robertson et al., 2014, pp. 92).

According to Ohm's law (Equation 3.1), force, deformation, resistance, and voltage are directly related (Robertson et al., 2014, pp. 92). Thus, the force applied to a force platform can be calculated by measuring the change in voltage in the circuit (Ramey, 1975; Robertson et al., 2014, pp. 92):

$$V = I \times R \tag{3.1}$$

where V represents the voltage output, I represents the current, and R represents the magnitude of the resistance (Robertson et al., 2014, pp. 348).

3.3 Piezoelectric

The piezoelectric effect is commonly defined as the generation of an electrical charge induced by a crystalline material (a form of solid material), as a response to alterations in shape (Ramey, 1975, pp. 307; Fraden, 2000, pp. 66). One of the materials which possess such piezoelectric characteristics is the quartz crystal (Ramey, 1975, pp. 307). The quartz crystal responds to e.g., shear stress by altering the orientation of the crystal body to that of the crystal axis (Ramey, 1975, pp. 307; Robertson et al., 2014, pp. 92).

In order to sense the electrical charge, electrodes must be placed on the surface of the crystal body (Fraden, 2000, pp. 67). Resultingly, the crystal performs in an electric circuit as a charge generator (produces electrical signals) and a capacitor (stores the electric charge) (Ramey, 1975, pp. 307; Fraden, 2000, pp. 67; Robertson et al., 2014 pp. 92).

Unlike the strain gauges, the voltage output of piezoelectric elements is given by the following equation:

$$V = \frac{Q}{C} \tag{3.2}$$

where C is the capacitance of the element, $Q = d_m F$ which is the charge induced by a force F in a direction perpendicular to the surface of the electrode, and d_m is the piezo coefficient for the respective material (Cross, 1999, pp. 305, Fraden, 2000, pp. 68–69).

Even though the associated electronic circuits differ between the piezoelectric and strain gauge force transducers, the concept is similar. An applied force causes deformation in the respective material, leading to an electrical response, which magnitude is directly proportional to the magnitude of the applied force (Browne & O'Hare, 2000, pp. 517; Robertson et al., 2014, pp. 92).

3.4 Strain gauges vs. piezoelectric

Whilst piezoelectric force transducers are known for their excellent linearity, range, sensitivity, as well as high-frequency responses (see information below), they cannot be easily adapted to surfaces due to their large size (Muro-de-la-Herran et al., 2014, pp. 3373; Robertson et al., 2014, pp. 94). Moreover, the voltage outputs from the piezoelectric force transducers are subjected to slow drift due to current leakage (Hall et al., 1996, pp. 659). These inherent limitations could explain why piezoelectric force transducers are not as commonly applied in force platforms, compared with strain gauges. In fact, to the author's knowledge, only one of the commercially available force platforms uses piezoelectric technology (Kistler). However, this force platform system is highly popular both in laboratory and in field settings (Bobbert & Schamhardt, 1990; Kibele, 1998; Baca, 1999; Vanrenterghem et al., 2004; Psycharakis & Miller, 2006; Meylan et al., 2011; Owen et al., 2014; Silveira et al., 2017; McGhie et al., 2019; Harry et al., 2020; Philpott et al., 2020; Kennedy & Drake, 2021; McMahon et al., 2022).

Strain gauges, on the other hand, are sensitive to low temperatures and rising humidity (Chockalingam et al., 2002, pp. 24; Keil, 2017, pp. 4). However, strain gauges present some advantages over piezoelectric transducers, such as better stability for long-term measurements (Silva et al., 2017, pp. 260). Moreover, their resolution is limited only by the instrumentation driving them (i.e., no need for a charge amplifier) (Roriz et al., 2014). These advantages might be the reason why most of the commercial force platform systems are built on strain gauge technology (Aragón-Vargas, 2000; Domire & Challis, 2007; Cormack et al., 2008; Wallace et al., 2010; Young et al., 2011; García-López et al., 2013; Whitmer et al., 2015; Read et al., 2016; Jiménez-Reyes et al., 2017; Lake et al., 2018;

García-Ramos et al., 2020; Janicijevic et al., 2021; Wilder et al., 2021; Lindberg et al., 2022).

Although there are clear differences in the technology employed to measure force, depending on if the force transducers use strain gauge or piezoelectric technology, no studies have tested the magnitude of the outcome differences, and their potential impact on performance variables measured by the force platform, such as jump height.

3.5 Force transducer qualities

The proportionality between the applied force and corresponding voltage output is affected by how accurately a force transducer transfers force to electrical voltage—which depends on the quality of the force transducer. For the purpose of this thesis, **quality** is defined as the force transducer's ability to transform the applied force into voltage.

Disregarding the underlying electrical details of the force transducers (explained above), what is of ultimate interest is the relationship between the applied force and the corresponding voltage output (Robertson et al., 2014, pp. 92–93).

Related to the relationship between the applied force and voltage output is the **linearity** of the force transducers. The linearity represents the Pearson product-moment correlation and indicates the strength of the linear relationship (Robertson et al., 2014, pp. 93). Previous studies have recommended the nonlinearity to be < 0.1% of the full-scale output (Brown & O'Hare, 2000, pp. 520), although linearity of < 0.2% of the full-scale output has also been accepted (Moir et al., 2009; Kons et al., 2018; Parker & Lundgren, 2018).

Voltage is converted into force using a calibration coefficient, also called the **sensitivity**. Good sensitivity is of importance, as it affects measurement accuracy (Robertson et al., 2014, pp. 93). Related to the sensitivity of the force platform, is the **range** of force that a transducer can measure before its response changes markedly. Force transducers are typically rated for a particular range where their force response is linear; the voltage output may saturate if higher forces are applied. A force transducer should have enough range for the forces one wishes to measure (Robertson et al., 2014, pp. 93).

3.5.1 Natural frequency

Any physical structure will characteristically respond to a forced vibration based on its inertial mass, elasticity, and damping. The two formers dictate the **natural frequency** of that structure. When an external vibration at or above the natural frequency is imposed, the structure will continue to produce force (Robertson et al., 2014, pp. 93). In biomechanics, this response is undesirable, as it amplifies the force response at that frequency (Robertson et al., 2014, pp. 94). Thus, an important aspect related to the force platform is its natural frequency. The natural frequency must be greater than the corresponding frequency of the signal to be measured (Ramey, 1975, pp. 316; Robertson et al., 2014, pp. 93; Silva et al., 2017, pp. 261).

Previous studies have stated that the natural frequency for impact forces, such as obtained when jumping, should be 10 times greater than the frequency of the impact (Ramey, 1975, pp. 316). Moreover, it has been recommended that a natural frequency of around 1000 Hz is desirable for most biomechanical applications (Psycharakis & Miller, 2006, pp. 517). Even though the natural frequency of the force platform is of importance for their quality, and has been discussed to be of importance when measuring high-impact movements such as jumping, the exact impact this factor has on performance outcomes such as jump height has never been directly examined.

In this project, the natural frequency was tested for the included force platforms by striking the platforms with a rubber mallet. During analyses, it became evident that natural frequency cannot be tested in portable force platform systems without anchoring them to the ground, which was not done in this project. Hence, for the purpose of this thesis, the results from the natural frequency testing are not presented nor discussed, although the reader should be aware of its potential influence. The reader is directed to *Appendix II* for a visual comparison of the frequency response of an in-ground force platform and a portable force platform.

3.6 Summary

The individual errors associated with the hardware components of the force platform are small and would arguably not influence any performance outcomes such as jump height measured by the force platform. However, Psycharakis & Miller (2006) observed that the accumulated error (the sum of several of the errors addressed above) was at least 8%. An error of such magnitude is however only an error of importance if all the factors addressed above affect performance outcomes such as a jump height. As of today, to what extent these errors affect jump height measured by a force platform, has not been examined.

Section 4 – Jump height calculations from force plate recordings

When jumping on a force platform, jump height is not directly measured but rather calculated from the GRF-time tracings. In this section, a brief overview of the calculation procedures needed to calculate jump height from the GRF-time tracings will be given. The section will outline different equations and data processing steps that are commonly reported to be used for jump height calculations, and the expected differences between these factors.

4.1 Equations used to calculate jump height

Jump height can be calculated from the GRF-time tracings measured by the force platform through different equations. The reason several equations exist to calculate jump height is due to a myriad of assumptions that do not necessarily hold true in all instances but are difficult to avoid in practice.

Jump height can simply be calculated from flight-time (i.e., time in the air), based on the following equation:

$$jump\ height\ = \frac{1}{2}\, g\ \times \left(\frac{t}{2}\right)^2 \qquad (4.1)$$

where $g = 9.81\text{m}\cdot\text{s}^{-2}$ and t = time in the air. Even though Equation 4.1 can be, and is, used to calculate jump height from force plate recordings (Asmussen & Bonde-Pedersen, 1974; Aragón-Vargas, 2000; Moir, 2008; Pérez-Castilla & García-Ramos, 2018; Wank & Coenning, 2019; Chiu & Dæhlin, 2020; Montalvo et al., 2021), it is used more frequently in technologies such as contact mats and smartphone applications, as this method does not directly rely on the GRF-time tracings, but simply the detection of take-off and landing (Bosco et al., 1983; Rago et al., 2018; Tenelsen et al., 2019; Montalvo et al., 2021).

Force platform systems typically use the impulse-momentum theorem to calculate jump height (Cavagna et al., 1971; Bosco & Komi, 1979; Harman et al., 1990; Dowling &

Vamos, 1993; Dias et al., 2011; Malisoux et al., 2017; Kons et al., 2018; Petridis et al., 2019; McHugh et al., 2020; Souza et al., 2020; Haugen et al., 2021; Kennedy & Drake, 2021; Lindberg et al., 2021; Pérez-Castilla et al., 2021; Lindberg et al., 2022).

The impulse-momentum theorem describes how the accumulation of force over time (impulse) creates a change in momentum (which is mass × velocity):

$$\int_{t_{start}}^{t_{end}} F\,dt = mv_{final} - mv_{initial} \tag{4.2}$$

where F = the sum of forces acting on the body ($GRFs + g$) recorded from the force platform, dt = difference in time, m = mass of the body, and v = velocity of the CoM.

To displace the CoM a distance h vertically, a certain amount of energy is needed. The total mechanical energy of the CoM is divided into potential and kinetic energy, where the horizontal partition of kinetic energy can be disregarded in a vertical jump. The vertical kinetic energy at take-off is transformed into potential energy in the flight phase of a jump. Hence, to jump as high as possible, the sum of the potential and the vertical partition of kinetic energy at take-off needs to be maximized. The vertical kinetic energy is in turn determined by the vertical velocity of the CoM (Bobbert & van Soest, 2001):

$$kinetic\ energy = \frac{1}{2}mv^2 \tag{4.3}$$

Thus, to increase jump height, the aim will be to increase the vertical velocity of the CoM at take-off.

The change in velocity of the CoM is the integral of its acceleration. According to Newton's 2nd law of motion, an increase in acceleration can be achieved by increasing the sum of forces acting on the body:

$$a = \frac{g + GRF}{m} \tag{4.4}$$

where a = acceleration of the CoM. The velocity of the CoM is then obtained by integrating acceleration over time:

$$v_{final} = v_{inital} + \int_{t_{start}}^{t_{end}} a\, dt \tag{4.5}$$

where v_{final} = velocity at take-off (for CMJs and SJs, at landing for DJs), v_{inital} = velocity at the start of integration (an illustration is given in Figure 6), t_{start} represents the start of integration, and t_{end} represents the stop of integration (at take-off; Figure 6). Hence, by measuring the GRFs during a jump, the velocity of the CoM can be computed.

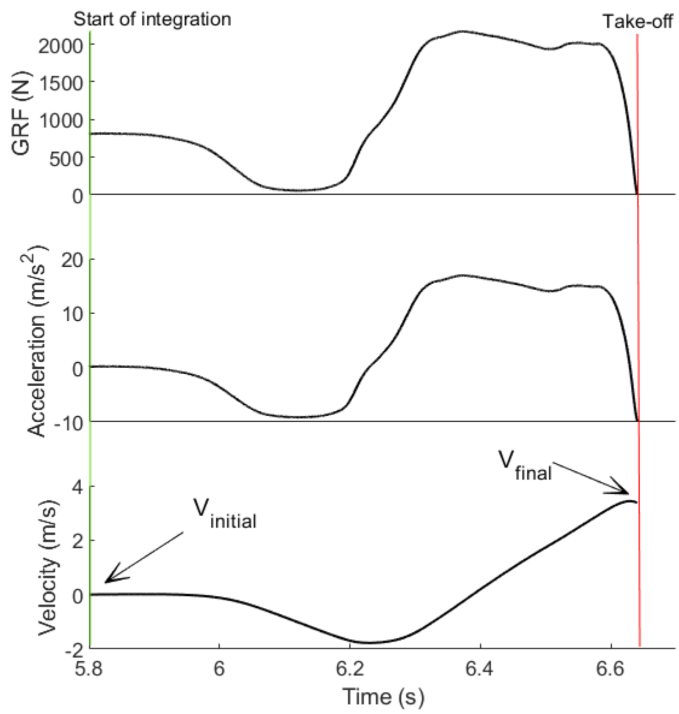

Figure 6. *Top graph: the ground reaction force (GRF in N), middle graph: acceleration (m/s^2), bottom graph: velocity (m/s). Plotted against time (s). Example from the start of integration until take-off in a countermovement jump. Green line: start of integration, red line: stop of integration at take-off. Arrows depict the initial and final velocity as an input to equation 4.5. Please see the text for further information. Own illustration made in MATLAB (R2021b version; Math-Works, Inc, Natick, MA).*

Using the relation between potential and kinetic energy of the CoM (principal of energy conservation; Equation 4.6a), jump height can be estimated using the velocity at take-off as the final velocity (assuming an initial velocity of 0 m·s^{-1}; Equation 4.5) by simply rearranging Equation 4.6a (Equation 4.6b).

$$mgh = \frac{1}{2}mv^2 \tag{4.6a}$$

$$h = \frac{v^2}{2g} \tag{4.6b}$$

where h = jump height.

Assuming an initial velocity of 0 m·s^{-1} is most easily achievable when performing the CMJ or the SJ. When performing a DJ, the initial velocity is not 0 m·s^{-1} before the jump as the person drops off a box prior to the jump. The initial velocity can be estimated from the assumed drop height (i.e., acceleration of CoM by gravity over the drop distance; Equation 4.6a), and with this information, rearranging Equation 4.6a to Equation 4.6b, using the *touchdown* velocity as a measure of initial velocity in Equation 4.5. However, this is not an easy task because the actual drop height of the CoM may not be the same as the height of the box from which the person drops (usually participants slightly lower or elevate their CoM when stepping off the box). To circumvent this issue some researchers have reported DJ height to be analyzed with the initial velocity of 0 m·s^{-1} taken from a period after the landing (if the person stands still), and from this, applying Equation 4.6b, starting integration from the end of the jump (Baca, 1999; Wank & Coenning, 2019; Jørgensen et al., 2021; McMahon et al., 2021; Wade et al., 2022). Calculating jump height backward in this manner has also been proposed for the SJ, as it may be difficult to achieve a steady stance in the squat position (Wank & Coenning, 2019; Wade et al., 2022).

In addition to the velocity at take-off being a direct input into Equation 4.6b, the velocity of the CoM can itself be integrated to obtain the displacement of the CoM, where we could either obtain the maximum displacement of the CoM during the jump (Equation 4.7a) or add the position of the CoM at take-off to Equation 4.6a (Equation 4.7b).

$$h = \max\left(\iint_{t_{start}}^{t_{landing}} a\,dt\right) \tag{4.7a}$$

$$h = \frac{v^2}{2g} + \iint_{t_{start}}^{t_{takeoff}} a\,dt \tag{4.7b}$$

Depending on the equation chosen large differences in jump height should be expected. The flight-time method (Equation 4.1) has been shown to overestimate jump height compared with using the take-off velocity (Equation 4.6b) by 0.6 to 4.1 cm (Kibele, 1998; Baca, 1999; Aragón-Vargas, 2000; Moir, 2008; Wank & Coenning, 2019; Chiu & Dæhlin, 2020; Lindberg et al., 2021). The overestimations observed when relying on flight-time to estimate jump height lie in the assumption that the time up to the highest point of the jump (apex) is of similar duration to the time down from the apex. This assumption rarely holds true as participants are likely to slightly bend their legs while in the air, which artificially increases flight-time and as such jump height (Kibele, 1998; Baca, 1999; Moir, 2008).

Additionally, both flight-time (Equation 4.1) and take-off velocity (Equation 4.6b) have been reported to significantly underestimate jump height compared with Equations 4.7a or 4.7b by up to ~ 19 cm, which is not surprising given that they neglect the displacement of CoM prior to take-off (i.e., heel-rise) (Wank & Coenning, 2019; Chiu & Dæhlin, 2020; Pinto & Callaghan, 2021). Hence, different equations should not be used interchangeably to calculate jump height.

4.2. Data processing steps

Regardless of the equation, data processing, which is needed when using GRFs to calculate jump height, has been shown to cause significant errors in jump height, in fact up to 26% (Street et al., 2001). The potential sources of errors can be divided into (1) measurement errors—regarding how the force data is collected from the force platforms, and (2) computational errors—regarding different calculating procedures in the equations above, needed to calculate jump height (Street et al., 2001).

4.2.1 Measurement errors

The measurement errors are affected by a) the sampling frequency of the force data (Street et al., 2001), b) the choice of applying a filter to the force data (Street et al., 2001; Pinto & Callaghan, 2021; Harry et al., 2022), and c) the cut-off frequency of that filter (Street et al., 2001; Pinto & Callaghan, 2021; Harry et al., 2022).

4.2.1.1 Sampling frequency

The sampling frequency refers to the frequency at which the signal from the force platform is sampled (Street et al., 2001; Hori et al., 2009). Street et al. (2001) recommended sampling with frequencies ≥ 1080 Hz for jump height assessments, as lower sampling frequencies significantly underestimated jump height, although the underestimation decreased with increases in sampling frequencies (4.4% at 180 Hz to 0.3% at 900 Hz). Yet, studies report sampling frequencies in the range of 100 to 2000 Hz for jump height assessments using force platforms, where the lower sampling frequencies are typically observed in portable force platform systems (Bobbert et al., 1996; Hatze, 1998; Aragón-Vargas, 2000; Moir et al., 2005; Domire & Challis, 2007; Cormack et al., 2008; Coh & Mackala, 2013; Centeno-Prada et al., 2015; Loturco et al., 2018; García-Ramos et al., 2020; Wilder et al., 2021; Lindberg et al., 2022).

4.2.1.2 Filtering the force data

Filtering is a process in which noise in the measurements is removed (Harry et al., 2022). When applying a low-pass filter, all data below the designated cut-off frequency will be retained for analysis, whilst the data above the cut-off frequency is removed as noise, and vice versa for high-pass filtering (Robertson et al., 2014; Harry et al., 2022). It has been recommended to treat the GRF-time data unfiltered for jump height assessments, as filtering the data was observed to cause significant underestimations in jump height, although one should note that these recommendations stem from laboratory in-ground force platforms (Street et al., 2001; Harry et al., 2022). Yet, studies report the force data to be filtered with cut-off frequencies ranging from 4 to 50 Hz when assessing jump height outcomes (Hasson et al., 2004; Moir et al., 2005; Barker et al., 2018; Philpott et al., 2020; Montalvo et al., 2021; Harry et al., 2022).

4.2.2 Computational errors

The computational errors are affected by e) method of integration (Street et al., 2001), f) start of integration (Street et al., 2001; Meylan et al., 2011; Pérez-Castilla et al., 2019; Donahue et al., 2021), g) direction of integration (Wank & Coenning, 2019, Wade et al., 2022), h) selection of take-off/landing thresholds (stop of integration) (Street et al., 2001; Pérez-Castilla et al., 2021), and i) averaging periods of body weight (Street et al., 2001).

4.2.2.1 Integration

If using the impulse-momentum theorem to obtain jump height (Equations 4.6a, 4.7a, or 4.7b), the force data must be numerically integrated over time in order to obtain velocity or displacement (once to get velocity, twice to obtain displacement). When integrating force over time, an approximation of the area under the GRF-time curve is obtained. Equation 4.1 is not reliant on integration procedures.

With regards to integration procedures, three steps must be considered: i) the integration method, ii) the start and stop of integration, and iii) the direction of integration. The end of integration is essentially at the point of take-off/landing and will therefore be discussed in conjunction with these points.

4.2.2.1.1 Method of integration

The difference between the various integration methods lies in how the area under the curve is divided into subintervals of different shapes. The trapezoid rule (trapezoids are fitted to each subinterval) applies a linear approximation, whilst Simpson's rule (parabolic shapes are fitted to each subinterval) applies a quadratic approximation (Kong et al., 2020). Due to this, Simpson's rule is generally viewed as superiorly accurate compared with a linear approximation, although the trapezoid rule is reported to be easier for software to handle (Robertson et al., 2014, pp. 88). Indeed, due to the latter, the most cited integration method in the jump height literature is the trapezoid rule (Moir et al., 2009; Dias et al., 2011; Nielsen et al., 2019; McMahon et al., 2021; Wade et al., 2022), although the Simpson's rule is also reported to be used (Meylan et al., 2011; Chiu & Dæhlin, 2020).

4.2.2.1.2 Start of integration

As of today, studies report integration to be started from: i) time thresholds (e.g., 2 s prior to the start of movement), ii) absolute thresholds (e.g., when the force is above or below 50 N), iii) relative thresholds (e.g., when the force is above or below 5% of body weight), or iv) a hybrid of a relative threshold (force above or below five standard deviations of body weight) going 0.3 s back in time. It has been recommended to start integration > 1 s prior to the start of movement (Street et al., 2001), at a relative threshold of 2.5% of body weight (Meylan et al., 2011), or apply the hybrid version (Pérez-Castilla et al., 2019; Donahue et al., 2021) as these methods retain more of the force signal for analysis, compared with starting integration at e.g., the start of movement. It remains unknown how most researchers chose to start integration, as this is rarely mentioned in the literature.

4.2.2.1.3 Direction of integration

Most studies report integration to be started from the beginning of the jump (forward integration procedures), but newer studies are suggesting how a backward integration procedure (that is, starting integration from the landing phase of the force data) could be a good option for certain jump modalities (e.g., SJ and DJ) (Wank & Coenning, 2019; Wade et al., 2022). For the DJ, the effect of integrating backwards might be a good option due to the challenge of correctly estimating initial velocity if only one force platform is available (estimating drop height from box height). For SJs, backward integration might be a good option due to the challenge of achieving a steady stance in squat position (Wank & Coenning, 2019; Lindberg et al., 2022), as integration should be initiated at a velocity of ~ 0 $m \cdot s^{-1}$. Moreover, if using Equations 4.7a or 4.7b for SJ height calculations (accounting for the heel-rise), a forward integration procedure would imply integrating the force from the upraised standing position, through the squat position (held for 1–2 s), until take-off. A longer integration time will cause noise in the data to accumulate to a larger degree (Wade et al., 2020). Thus, for Equations 4.7a or 4.7b backward integration has been recommended for SJ height calculations (Wank & Coenning, 2019; Wade et al., 2020).

A recent study compared forward integration to backward integration procedures for CMJ height measures and found the latter to be equally accurate though displaying slightly larger variability in jump height (Wade et al., 2022). Thus, it seems as though backward integration is a valid option for CMJ, SJ, and DJ analyses, although future studies are encouraged to support these recommendations.

4.2.2.2 Take-off thresholds

Two studies have investigated the effect of different take-off thresholds on jump height, for loaded and unloaded CMJs. From these studies, two take-off definitions have been recommended. First, it has been recommended to define take-off as the first force value that reaches a value that is lower than the maximum difference between the average GRF during flight phase and 0 N (peak residual force (PRF) method) (Street et al., 2001; Pérez-Castilla et al., 2021). Secondly, take-off has been recommended to be identified as the first instance where the GRF exceeds mean vertical GRF during the flight phase plus five standard deviations (5SD method) (Pérez-Castilla et al., 2021).

In both the studies by Street et al. (2001) and Pérez-Castilla et al. (2021), it was observed that when the take-off threshold increased from 2 N to 10 N, jump height was significantly overestimated by up to 4% (unloaded jumps: 6 N = 1.0% overestimation, 10 N = 1.5% overestimation (Street et al., 2001); loaded jumps: 10 N = 4% overestimation compared with the 5SD method, 3% overestimation compared with the PRF method (Pérez-Castilla et al., 2021)). Yet, in the literature, take-off thresholds of 4 N (Harrison et al., 2019), 5 N (Pérez-Castilla & García-Ramos, 2018), 10 N (Malisoux et al., 2017; Janicijevic et al., 2021; Lindberg et al., 2021), 20 N (Barker et al., 2018; Chandler et al., 2018; Guess et al., 2020; Heishman et al., 2020; Harry et al., 2022), 30 N (Merrigan et al., 2020), and even 40 N (Vanezis & Lees, 2005) have been reported to be used for jump height calculations.

4.2.2.3 Averaging periods of body weight

One study has investigated the effect of different procedures on averaging body weight. Street et al. (2001), recommended averaging body weight over a $\geq$ 1 s period prior to the start of movement, as shorter averaging periods increased the random error ($\pm$ 1.4% at 0.5 s to $\pm$ 3.3% at 0.1 s). It remains unknown how most researchers chose to obtain body weight, as this is rarely mentioned in the literature.

4.3 Summary

The simplest and most popular way of analyzing a jump on a force platform is to extract the variables of interest from a designated software. Using the software requires limited time, effort, and knowledge of any of the calculation procedures discussed above needed to obtain jump height (Hébert-Losier & Beaven, 2014; Harry, 2021). However, with the convenience of the software, a black box phenomenon is created where the user has limited information on how jump height has been calculated. Considering the differences in jump height when using different equations and/or different data processing steps, one should expect the software calculations to be neither accurate nor comparable to other software calculations.

Section 5 – Kinematics

The force platform is the measurement system of interest in this thesis. However, the force platform measures force, and thus does not directly measure the outcome variable of interest—jump height.

To date, the most direct measure of jump height is obtained by tracking the displacement of the CoM during a jump. The most accurate, but still practically feasible, way of obtaining the CoM position is through 3D motion capture. By measuring the position of the CoM directly, challenges associated with detecting proper initial conditions and integration drifts are avoided. In this thesis, a measure of the CoM trajectory obtained using a 3D motion capture system was included. 3D motion capture was included as an alternative reference, free of any inherent limitations of the force platform itself. However, in order to obtain the CoM displacement from 3D motion capture, the body is assumed to consist of rigid geometrical objects. Thus, even though jump height is measured more directly through 3D motion capture modeling, the outcome variable is based on assumptions that are not needed when jump height is calculated using the GRFs.

The purpose of this section is to provide the reader with brief information on the workings of the 3D motion capture system and how it is used to generate the whole-body CoM. The focus will be on the principles applied to the CoM approach used in this thesis.

5.1 The center of mass

The CoM is commonly defined as the position of a point at which a motionless system, if supported at that point, will remain balanced. It can also be referred to as the balance point of the body (Robertson et al., 2014, pp. 69) (Figure 7).

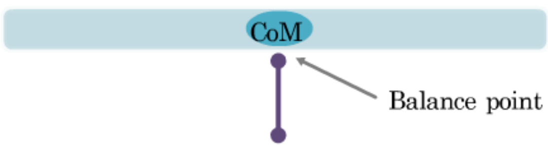

Figure 7. *An illustration of the location of the center of mass (CoM) in a rigid construction. The CoM is depicted as a blue circle located in the middle of the rigid construction. The point in which the purple line meets the CoM illustrates the balance point of the rigid construction (i.e., the location of the CoM). Own illustration made in Focusky v.3.7.7. (Focusky Software Co., Ltg, Hong Kong).*

5.1.1 Estimating the center of mass by a rigid segment model

The whole-body CoM is defined as the average position of all the parts of a particular system, weighted according to the mass of each included system part. The whole-body CoM is computed example vice as follows:

$$\frac{(S_m1 \times S_{com}1) + (S_m2 \times S_{com}2) + (S_m3 \times S_{com}3) + (S_m4 \times S_{com}4) \ldots}{total\ body\ mass} \quad (5.1)$$

where S_m1 represents the segmental mass of segment 1, S_m2 represents the segmental mass of segment 2, and so on. $S_{com}1$ represents the location of the center of mass of segment 1, $S_{com}2$ represents the location of the center of mass of segment 2, and so on (Robertson et al., 2014, pp. 69).

As seen from Equation 5.1, the heavier the segment (i.e., the greater the segmental mass) the more it contributes to the whole-body CoM. In humans, the whole-body CoM is typically located approximately around the umbilical region, which centers around the heavier areas of the body (thighs and trunk) (Robertson et al., 2014).

5.1.2 Segmental parameters

As seen from Equation 5.1, the segmental parameters pertinent for CoM computations are the segment mass and the location of each segment's center of mass.

Each individual segment mass is defined as the proportion that each segment contributes to the total body mass (Robertson et al., 2014, pp. 69). The location of each individual segment's center of mass is defined as a point located at a certain percentage relative to the defined endpoint (Robertson et al., 2014, pp. 70).

The segment mass and the segment center of mass are unattainable through standard ethical, non-laborious, test procedures. Segmental parameters have thus been quantified through other methods, which have been divided into four categories (Robertson et al., 2014, pp. 63):

- Cadaver material.
- Mathematical modeling.
- Scanning and imaging.

- Kinematic measures.

For whole-body CoM computations, the most common and frequently cited method used to acquire these segmental parameters stems from the monograph published by Dempster in 1955. In the monograph by Dempster (1955), the segmental parameters were derived from cadaver material. More specifically, eight cadaver Caucasian males around 52 to 83 years were used to obtain the segmental parameters. For the purpose of this thesis, the whole-body CoM was obtained using the Visual 3D software. The Visual 3D software uses the Dempster model to obtain the segmental parameters and its limitations will therefore be addressed later in this section.

5.2 Motion capture systems

Three-dimensional motion capture systems work by tracking either retroreflective (passive) markers or light-emitting (active) markers, placed on various anatomical landmarks (Pueo & Jimenez-Olmedo, 2017). For this thesis, passive-reflective markers were used.

For a whole-body capture, there is a necessity for around 40 markers, usually placed in clusters at different body segments (Chiari et al., 2005). To estimate the CoM for each joint segment, there should be at least three markers on each segment. The passive-reflective markers most commonly used in sports biomechanics are skin-based markers—that is, markers are placed on the skin to represent the underlying bone (Chiari et al., 2005; Leardini et al., 2005; Schallig et al., 2021). The limitations of skin-based markers are addressed below. For the purpose of this thesis, 76 passive-reflective markers, including clusters and individual markers, were used.

Each marker must be captured by two cameras to determine its 3D position. However, due to the nature of most movements (e.g., arm swings) current guidelines state that eight or more cameras are needed to gain a whole-body capture (Chiari et al., 2005; Pueo & Jimenez-Olmedo, 2017). For the purpose of this thesis, 24 cameras (for 14 participants) or 15 cameras (for 13 participants) were used.

5.3 Limitations of CoM modeling

When estimating whole-body CoM using 3D motion capture, there are essentially two points of interest: (1) the estimated segment parameters which are then related to (2) each segment's position and orientation. How accurately each segment's position and orientation has been estimated is affected by the workings of 3D motion capture in general and will be addressed briefly first.

5.3.1 Marker placement

As markers are placed to define anatomical segments, the sensitivity of kinematic outcomes to marker placement is inevitable. Indeed, errors in marker placement have shown alarming effects on kinematic outcomes, though mostly on joint angle outcomes (McCahill et al., 2021). As of today though, the specific sensitivity of kinematic variables to differences in marker placement remains unclear. The effect of marker placement on kinematic outcomes will vary depending on the reported variable, the magnitude of displacement of the segment, and the movement phase being analyzed (McFadden et al., 2020).

For the protocol of this thesis (**Part III**), the markers were placed on anatomical landmarks, through palpation and visual inspection. It is not necessarily easy to find the correct endpoint of different segments, both within an individual as well as in different participants. For example, some areas of the body are difficult to palpate correctly, e.g., the hip and shoulder joint, and more so in certain individuals—which is even true in fit individuals who were included in this thesis.

Even though the whole-body CoM is potentially less affected by the sensitivity of marker placement, several participants (*n* = 20) were examined in this thesis, and some of the participants performed the protocol on more than one occasion (**Part III**). Thus, it was deemed important that the marker placement was consistent between participants. Therefore, markers were placed on the participants by the same person. As this thesis did not aim at measuring test-retest reliability, or joint angles, it is believed that the CoM model was minorly affected by the sensitivity of the marker placement.

5.3.2 The soft tissue artifact

Skin-based markers are placed on anatomical landmarks under the assumption that these markers accurately represent the motion of the underlying bone—an unfortunate assumption. There is soft tissue (skin, fat, and muscles) that lies as an envelope between the marker and the underlying bone. During movements, the soft tissue will move relative to the bone and consequently, so will the markers (Leardini et al., 2005). The displacement of the markers relative to the bone represents an artifact, the soft tissue artifact, which is a well-known source of error in skin-based marker motion analysis (Leadini et al., 2005; Shallig et al., 2021). As with marker placement, the effects of the soft tissue artifact have mainly been discussed in relation to joint angle outcomes (Gruber et al., 1998; Leardini et al., 2005). It is believed that the soft tissue artifact affected the whole-body CoM analysis minimally in this project, although one should be aware of its existence.

5.3.3 Rigid body modeling

An important assumption when computing the whole-body CoM, is that each of the segments of the body are assumed to be rigid, and thus unable to change shape. This assumption does not hold true as it neglects movements in the muscles (contraction), ligaments (stretched), blood (flowing), and even bones (bending), which do occur during human movements (Robertson et al., 2014, pp. 63). The rigid-body assumption is a major limitation for whole-body CoM computations, using 3D motion capture.

5.3.4 Methods for deriving segmental parameters

Averaging segmental parameters from dead, old, Caucasian males, is clearly not generalizable to many populations. For these reasons, other, presumably more generalized methods for obtaining the segment mass and segment center of mass have been computed.

First and foremost, Zatsiorsky and Seluyanov (1983) provided alternatives to the cadaver-derived segmental parameters. In the study by Zatsiorsky and Seluyanov (1983), a gamma-ray scanning method was used to determine, among other things, the segment mass and segment center of mass of 100 male and 15 female participants (Caucasian, average age: 24 (males) and 19 (females)). The study by Zatsiorsky and Seluyanov was the first study providing information on segmental parameters in healthy young living adults, males and females, yet has rarely been chosen over cadaver data studies. de Leva (1996) discussed how this could mirror some limitations of the method provided by Zatsiorsky and

Seluyanov and provided adjustments to the described method. In short, the adjustment was based on using joint centers, rather than bony landmarks, to accurately locate each segment's center of mass. Using bony landmarks (which was the method originally applied by Zatsiorsky and Seluyanov (1983)) would cause significant decreases in the distance of the reference point to that of the endpoints of the segments when the joints were flexed, e.g., during movements. Yet, the method of Zatsiorsky and Seluyanov (1983), later adjusted by de Leva (1996), has rarely been chosen over cadaver studies.

In a study by Virmavirta and Isolehto (2014) the method by Dempster (1955) and the method by Zatsiorsky and Seluyanov (1983) (later adjusted by de Leva (1996)) were compared against a high-accuracy reaction board. The high-accuracy reaction board is the assumed "gold standard" for the whole-body CoM computations, though only measuring CoM in one anatomical position (Virmavirta & Isolehto, 2014). In the study by Virmavirta and Isolehto (2014), 82 young participants (around 23 to 26 years) were included ranging from athletes, physically active students, and sedentary individuals, including males and females. The main results regarding the difference between the Dempster method and the Zatsiorsky and Seluyanov method were that the Dempster method was not suited for physically active young men and provided even larger errors in females, as well as providing large errors for high jumpers, though somewhat more accurate results for gymnasts and throwers. The Zatsiorsky and Seluyanov method worked well with male students and high jumpers, but not with females. For ice hockey players and ski jumpers, neither of the methods provided acceptable results compared with the criteria. Even though the results from this study cannot be fully interpreted without accounting for its limitations, mainly how the measurements were conducted in a single anatomical posture (not during movements), it emphasizes the importance of applying an appropriate model for motion analysis.

5.4 Summary

Calculation of jump height using kinematic 3D modeling has its clear limitations. It is therefore not obvious that calculating jump height by estimating the displacement of the CoM through 3D motion capture is better suited for jump height measures than the force platform system.

Section 6 – The experimental approach of this thesis

In this project, we assumed that jump height would differ when measured by various force platform systems. We questioned what the magnitude of these differences would be and the reasons for any differences.

6.1 Study ethics

The experimental study in **Part III** was approved by the ethics committee at the Norwegian School of Sport Sciences, accepted by the Norwegian Center for Research Data, and performed according to the Declaration of Helsinki (approval IDs in **Part III**).

6.2 Participants

For the experimental study, a total of 27 participants were included (age: 26.2 ± 3.8 years, height: 1.76 ± 0.08 m, body mass: 73.2 ± 11.2 kg), both males (n = 17) and females (n = 10). Participants were free from any injury that could hinder them from performing maximal jumps. The recruitment was based on a convenience sample, although we wished to include participants with various body weights and jump performances.

The focus of this thesis was on the force platform systems, not on the performance of the jumper *per se*. Therefore, the share number of jumps performed on each force platform system (~ 200 jumps) and the range of jump heights (up to ~ 70 cm) were considered, and not the number, or specific characteristics of the participants. Our methodological approach complied with these terms.

6.3 Experimental approach

A concurrent validity approach was chosen where several portable force platform systems were compared against an in-ground force platform system (the reference). Both the hardware and software were included in the comparative analyses. A concurrent validity approach assumes that the set reference is the "gold standard" (Thomas et al., 2015, pp. 204). The portable systems were placed on top of the in-ground force platform, enabling concurrent jump measurements. The concurrent validity setup in this study eliminates biological variation which would be present if the jumps were performed on each force platform system separately. CoM modeling was included, which was free of any inherent limitations of the force platform (although not free of errors itself). Note that the CoM model was only compared with our reference calculation obtained from the reference system and to each of the proprietary software calculations (description in **Part III**).

We aimed to include the typical jump tests reported in the literature and used when assessing athletes, which were the CMJ, SJ, DJ, multi jumps, and loaded jumps (in this project performed as CMJs with a trap bar). For the purpose of this thesis only the CMJs, SJs, and DJs were analyzed. The jumps were performed as submaximal and maximal effort jumps, with and without the use of arms, and the DJs were performed from three drop heights where three different instructions were given (description in **Part III**). This approach was chosen mainly to obtain a large range in jump heights, as well as different types of GRF-time curves. Thus, for the three jump types (CMJs, SJs, and DJs) all sub-jump-type variants were pooled for statistical analysis.

As described in *sections 3 and 4*, any differences between force platform systems could be attributed to different hardware, and/or different software (algorithms used to calculate jump height). To eliminate these two sources from each other to the best of our ability, the following approach was used (which is given in more detail in **Part III**):

The raw force data obtained from both force platform systems concurrently were extracted and analyzed through the same algorithm. This is referred to as Hardware analysis in **Part III** as it eliminates the effect of different calculation procedures (e.g., different definitions for take-off thresholds).

Static testing was conducted to supplement the discussion on differences in hardware. The static testing which was performed were:

- Loading and unloading of known weights.
- Natural frequency response.
- Drift measures.

For the purpose of this thesis, only the results from the loading and unloading test are presented. The reader is directed to *Appendix II* for information on the natural frequency procedure used in this project.

Additionally, the force data from each portable system was calculated with our reference calculation (the calculation used in the Hardware analysis) and compared with the calculation of the proprietary software. This is referred to as Software analysis in **Part III** as we were addressing differences in calculation choices.

For the Hardware and Software analyses, we assessed the differences between the portable force platform systems and the set reference. Thus, the comparisons between the portable force platform systems were based on the deviation from the set reference system.

The limitations of the chosen experimental approach are discussed in **Part III**.

Part III – Article

Title: Jump Height Measured by Different Force Platform Systems – Are the Results Comparable?

Abstract

Purpose: To compare jump height measured by four portable force platform systems. **Methods:** The portable force platform systems Kistler, ForceDecks, MuscleLab, and HurLabs, were placed on top of an in-ground reference force platform (AMTI) to measure the ground reaction forces (GRFs) concurrently during a jump. Squat jumps, countermovement jumps, and drop jumps were analyzed. 3D motion capture was collected simultaneously. The raw force data obtained from both force platform systems concurrently were extracted and analyzed through the same algorithm (set as reference calculation; Hardware). Moreover, the GRFs measured from the portable force platforms were calculated with the reference calculation and their software calculation to obtain jump height (Software). **Results:** For all jump modalities, the systematic difference in jump height between the portable systems and the reference system ranged from −2.9% to 3.8% for the Hardware analysis, and from −11.6% to 11.1% for the Software analysis. The typical error of estimate (%) ranged from 1.1% to 5.0% for the Hardware analysis, and from 3.2% to 22.3% for the Software analysis. For all jump modalities and analyses, all force platform systems differed significantly from each other ($p \leq 0.05$). **Conclusions:** Even when applying identical jump protocols and calculation procedures, there were differences in jump height measured by different force platform systems. Different force platform systems should be used interchangeably in this way, with caution. Software calculations should not be expected to be accurate, and different software cannot be used interchangeably for jump height measures if accuracy of less than 2 ± 2 cm is of importance. The results of this study are useful to understand and interpret jump height measured from different commercial force platform suppliers.

Keywords: countermovement jump, squat jump, drop jump, testing, ground reaction force, hardware, software

Introduction

Maximal vertical jump height is presumably the most popular generic performance variable reported in the sports science literature (McMaster et al., 2014; Kozinc et al., 2021). Much of this popularity stems from the fact that jump height serves as a simple indicator of our ability to oppose gravity (Newton's 2nd law ($F = m \cdot a$))—which is fundamental for most sports performances (Cronin et al., 2004; Cormack et al., 2008; Jiménez-Reyes et al., 2017; Rago et al., 2018; Montalvo et al., 2021).

Three types of vertical jump tests are commonly used: the squat jump (SJ), the countermovement jump (CMJ), and the drop jump (DJ). Whereas SJ assesses concentric force development, CMJ and DJ challenge the ability to pre-load the muscle-tendon system with a countermovement prior to the concentric contraction (i.e., a plyometric contraction) (Bobbert et al., 1986; Bobbert & Casius, 2005). The countermovement is naturally employed in sports as it enhances one's ability for propulsive actions and, thus, to jump as high as possible. A CMJ is typically 5% to 10% higher than a SJ (Bobbert & Casius, 2005; Van Hooren & Zolotarjova, 2017; Kozinc et al., 2021; Seiberl et al., 2021). From an individually ideal drop height (usually 40–60 cm), DJ heights tend to be 1% to 14% higher than CMJ heights, as the drop optimizes the mechanical energy output via elastic properties in the muscle-tendon-complexes in the lower extremities (Bosco & Komi, 1979; Asmussen & Bonde-Pedersen, 1974; Lees & Fahmi, 1994).

Jump height can be measured by different technologies and methods—ranging from laboratory equipment, such as three-dimensional (3D) motion capture and high-end 3D force platforms (Montalvo et al., 2021; McMahon et al., 2022), to portable solutions, such as portable force platforms (Heishman et al., 2020), contact mats (Bosco et al., 1983), photoelectric cells (Glatthorn et al., 2011), or smartphone applications (Balsalobre-Fernández et al., 2015), to a single chalk (the jump and reach test) (Niering & Muehlbauer, 2021). Of all the available technologies and methods, the force platform is arguably the device that could give the most valuable information obtained from a vertical jump. The force platform is the only technology that allows a comprehensive analysis of the kinetic aspect of a jump, i.e., the forces involved in producing the jump (Beckham et al., 2014).

In its simplest form, a force platform is a device that records the ground reaction forces (GRFs) during a jump. From the GRFs, movement strategies and performance variables, such as jump height, can be calculated by laws of Newtonian physics (Linthorne, 2001; Beckham et al., 2014). In short, jump height is determined by the force impulse after subtracting body weight (Linthorne, 2001; Beckham et al., 2014).

Indeed, force platforms are considered the "gold standard" for force measurements during movements such as jumping by most sports scientists and practitioners (Cronin et al., 2004; Moir et al., 2009; Glatthorn et al., 2011; Buckthorpe et al., 2012; Castagna et al., 2013; Owen et al., 2014; Balsalobre-Fernández et al., 2015; Rago et al., 2018; Montalvo et al., 2021). Especially in the aftermath of force platforms becoming portable and more affordable (during the last two decades), there has been an exponential growth in the use of force platforms for jump testing across a variety of in-field settings, which is in addition to more conventional research settings (Chavda et al. 2018; McMahon et al., 2018; Pérez-Castilla et al., 2021). Yet, the "gold standard" status of the force platform has been questioned and claimed to stem more from its widespread use, rather than any direct evidence of its accuracy (Street et al., 2001; Psycharakis & Miller, 2006).

The accuracy of the force platform system for calculating jump height is potentially affected by several factors, which are summarized in Figure 1, but the overarching factors are the hardware and the software.

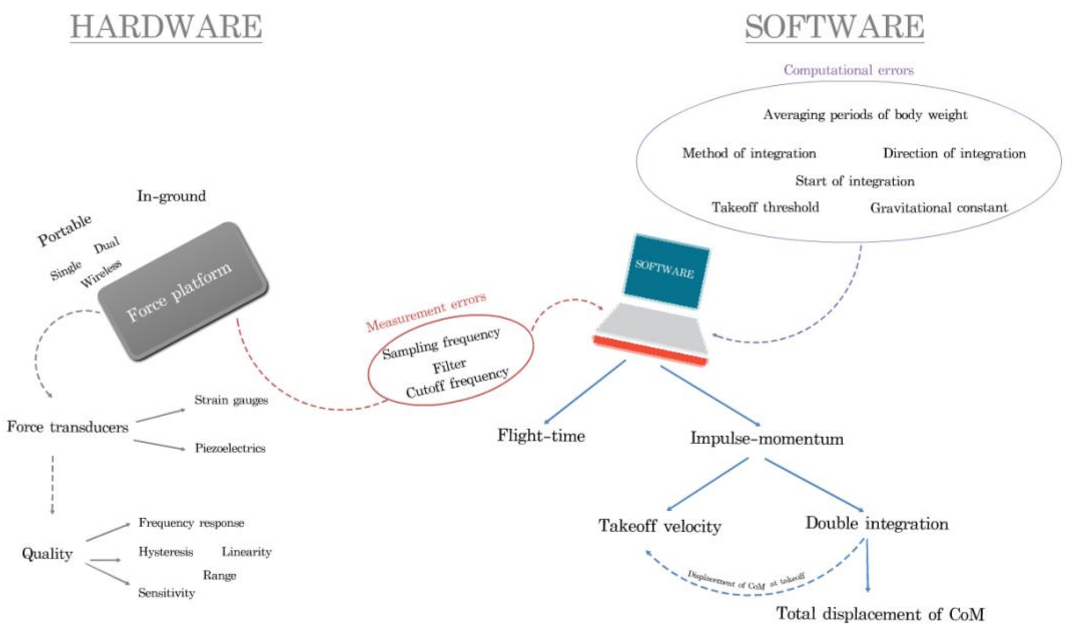

Figure 1*. An illustration of the potential sources of errors in a force platform system that could affect jump height. Jump height can be calculated from the flight-time, takeoff velocity, or displacement of the CoM from the software. Please see the text for further information. Own illustration made in Focusky v.3.7.7. (Focusky Software Co., Ltg, Hong Kong).*

1.1 The Hardware

Five previous studies have addressed the validity of a portable force platform system against an in-ground reference platform for jump assessments, where the latter is commonly considered superiorly accurate when compared to a portable system (Walsh et al., 2006; Buckthorpe et al., 2012; Silveira et al., 2017; Lake et al., 2018; Raymond et al., 2018). One study investigated the DJ (Walsh et al., 2006), whilst four analyzed the CMJ (Buckthorpe et al., 2012; Silveira et al., 2017; Lake et al. 2018; Raymond et al., 2018). Of the five studies, two reported jump heights from the CMJ, both with an excellent agreement (Buckthorpe et al., 2012; Lake et al., 2018). However, one of these studies compared the portable system to a reference in-ground force platform in a block randomized order and extracted jump height from two different software (Buckthorpe et al., 2012). This type of study design does not allow discriminating between the potential sources of errors, i.e., biological variation and differences in jump height calculations, and the actual accuracy of the portable system itself. Thus, to date, only a single study has reported the concurrent validity of a portable force platform for obtaining CMJ height (Lake et al., 2018), which is surprising considering the number of commercial force platform systems available for jump testing.

A force platform works by estimating the applied forces from changes in the voltage output of force transducers, which are embedded in the force platform. Force can be estimated in this manner as changes in voltage are directly proportional to the magnitude of the applied force (Robertson et al., 2014). However, the accuracy of the estimates depends on the qualities of the force transducers (Figure 1) (Psycharakis & Miller, 2006; Robertson et al., 2014). Psycharakis & Miller (2006) excessively studied the qualities of piezoelectric force transducers (Kistler force platform) and found an accumulated error of 8%. Hitherto, no studies have addressed whether the qualities of the commonly used force platform systems are at all related to the GRFs, and ultimately jump height during jump tests.

1.2 The Software

As illustrated in Figure 1, several steps are needed to calculate jump height from the GRFs, and previous studies have addressed how differences in these calculation steps may significantly impact jump height calculations. For instance, the flight-time and impulse-momentum methods have been found to yield quite different results in jump heights, ranging from 0.6 to 14 cm (Aragón-Vargas, 2000; Moir, 2008; Pérez-Castilla & García-Ramos, 2018; Wank & Coenning, 2019; Chiu & Dæhlin, 2020; Wade et al., 2020).

Most force platform systems apply the impulse-momentum theorem to calculate jump height. However, using the impulse-momentum theorem different calculations paths (equations) can be chosen, and jump height outcomes may differ by > 10 cm depending on the equation chosen (Aragón-Vargas, 2000; Moir, 2008; Pérez-Castilla & García-Ramos, 2018; Wank & Coenning, 2019; Chiu & Dæhlin, 2020; Wade et al., 2020).

Regardless of the equation, data processing, which is needed when using GRFs to calculate jump height, has been shown to cause significant errors in jump height, in fact up to 26% (Street et al., 2001). The potential sources of errors in the data processing include factors such as: a) sampling frequency of the force data (Street et al., 2001), b) the choice of applying a filter to the force data, and the cut-off frequency of that filter (Street et al., 2001; Pinto & Callaghan, 2021; Harry et al., 2022), c) method of integration (Street et al., 2001), d) start of integration (Street et al., 2001; Meylan et al., 2011; Pérez-Castilla et al., 2019; Donahue et al., 2021), e) direction of integration (Wank & Coenning, 2019; Wade et al., 2022), f) selection of take-off/landing thresholds (i.e., integration stop) (Street et al., 2001; Pérez-Castilla et al., 2021), and g) averaging periods of body weight (Street et al., 2001).

With the convenience of the software, a black box phenomenon is created giving us limited information on how jump height has been calculated (Hébert-Losier & Beaven, 2014; Harry, 2021). Considering the reported differences in jump height, depending on the different calculation steps, this is problematic. To date, no studies have investigated the jump height calculation accuracy of the commercially available software—thus, we cannot on any ground state that the software calculations are accurate.

Several different force platform systems, with their designated hardware and software, are reported to be used, and results obtained by different force platform systems are often compared between research and testing facilities. The purpose of this study was therefore to compare jump height measured by four different force platform systems and to examine whether differences in jump height could be attributed to the systems' hardware or software. Jump height was measured from the SJ, CMJ, and DJ. We hypothesized that there would be significant differences in jump height measured by different force platform systems. Further, we hypothesized that these differences would primarily be attributed to the different software (different algorithms used to calculate jump height) and to a lesser extent hardware differences.

Methods

2.1 Experimental Approach

This study is part of a project comparing jump height and other pertinent jump variables measured by several different force platform systems. To mirror the typical jump tests reported in the literature and used when assessing athletes, the included jumps were the CMJ, SJ, DJ, multi jumps, and loaded jumps (performed as CMJs with a trap bar). For the purpose of this study, the CMJs, SJs, and DJs were analyzed.

Different portable systems were compared against three in-ground reference force platforms (AMTI; Advanced Mechanical Technology, Inc, Watertown, MA 02472, US). The portable force platform systems used in this study were Kistler (Kistler Instruments Inc., Amherst, NY, USA), ForceDecks (Vald performance, Pty Ltd, Newstead QLD, Australia), MuscleLab (MuscleLab; Ergotest Innovation AS, Langesund, Norway), and HurLabs (HUR lab Oy, Kokkola, Helsinki, Finland). More information on the force platform systems is provided below. Both the hardware and software of these systems were included in the comparative analyses. By including these systems, we obtained single and dual force platform systems of various sizes, as well as force platforms with different force transducer technologies (Figure 1). To validate each of the portable systems, we simultaneously collected force data measured during a jump from a portable force platform placed on top of an in-ground reference force platform. Additionally, 3D motion capture, using full-body kinematics, was collected to obtain the whole-body center of mass (CoM) trajectory. The CoM analysis was included as an alternative reference to that of the in-ground force platform.

For the CMJs and SJs, we included submaximal and maximal jump heights, as well as jumps performed with and without the use of the arms. For the DJs, we included submaximal and maximal jump heights obtained from three drop heights, where the participants were given three different drop instructions. These jumps were chosen as an approach to encompass the typical range of jump height values reported in the scientific literature, and from years of experience with testing athletes (~ 10 to 70 cm), as well as to obtain different types of GRF-time curves measured from the same jump modality.

2.2 Participants

Twenty-seven participants (age: 26.2 ± 3.8 yrs, height: 1.76 ± 0.08 m, body mass: 73.2 ± 11.2 kg) were included in this study (males: n = 17, females: n = 10), and all were regularly active from a variety of sporting backgrounds. The study was approved by the ethical committee at the Norwegian School of Sport Sciences (reference ID: 187–170621) and accepted by the Norwegian Center for Research Data (reference ID: 492164). All participants gave written consent to participate in the study.

2.3 Equipment and Setup

The data collection took place in the biomechanics laboratory at the Norwegian School of Sport Sciences. Detailed information about the force platform systems included in this study is given in Table 1.

The portable force platform systems were placed on top of the reference in-ground force platforms for concurrent GRFs measures during jumps. We aimed at placing the portable force platforms at a stable location. Tape was placed on the reference platforms, on the locations where the portable systems should be set. This was to ensure that the portable systems remained on stable ground for the different test days/participants and to control whether the portable platforms shifted location during a jump. The portable systems were also jiggled when placed on the reference force platform to ensure a stable base.

Three-dimensional kinematic data were captured using 24 Qqus cameras (Qualisys AB, Gothenburg, Sweden) for 14 participants (8 in the 700 + series, and 16 in the 400 series) or 15 Qqus cameras for 13 participants (5 in the 700 + series, and 10 in the 400 series), sampling at 200 Hz. The system was calibrated according to the manufacturer's recommendations. Calibration accuracy (standard deviation of the calibrating wand length) was < 1.2 mm for all trials.

Table 1. *Hardware information for the included force platform systems.*

Model	**AMTI LG6-4-1**	**Kistler 9286BA**	**ForceDecks FDLite 03-94485**	**Musclelab 6FPL02**	**HurLabs FP4**
Dimensions (cm)	120 × 60	60 × 40 × 3.5	48.5 × 30 × 5.5 (× 2)	60 × 40 × 6	61 × 61 × 6
Type	In-ground	Portable	Portable	Portable	Portable
Nr	Single	Single	Dual	Single	Single
Force transducers	Strain gauges	Piezoelectric	Strain gauges	Strain gauges	Strain gauges
Sampling frequency (Hz)	2000	1000[a]	1000	200[b]	1200
AD-converter	16-bit	16-bit	16-bit	−	16-bit
Voltage range (V)	± 10	± 10	4.5−5.5	−	−
Software	−	MARS v.2.1.0.8	ForceDecks Software v. 2.0.8000	MuscleLab Software v. 10.221.100.0	Software Suite v. 3.8.0.2
Extension frames	−	No	Yes	No	No[c]

Abbreviations: cm, centimeters; Hz, hertz; V, voltage; v, version. [a]Kistler sampled at 1000 and the software offered to resample the data to 2000 Hz. 1000 Hz was the sampling frequency chosen in this study. [b]MuscleLab sampled 200 Hz and the software offered to resample the data, using spline integration, to 1000 Hz. 200 Hz was the sampling frequency chosen for this study. [c]HurLabs offers extension frames for their force platforms, but these had not been purchased for the force platform used in this study.

2.4 Test Procedures

The participants were instructed to wear shoes and clothing suited for jumping. The participants included in the CoM analysis ($n = 20$) were asked to wear shorts and upper-body wear suited for the marker-set.

First, the marker-set was placed on the participants. A full-body marker set was used, incorporating 76 passive spherical reflective markers (12 mm) on various anatomical and tracking landmarks. The marker-set was placed on the different participants by the same test leader.

Next, a brief warm-up was performed including 5 min bicycling on an ergometer bicycle (Keiser M3i, Keiser Corporation, Fresno, CA) with a self-selected cadence, followed by 10 repetitions of body weight squats, and 10 submaximal vertical jumps.

Please see Figure 2 for an overview of the included jumps in the protocol. The order of the jumps was randomized for each participant, but the protocol started with either the CMJ or SJ. For these jumps, it was randomized whether the jumps were performed with or without the arms first. All DJs were performed with arms on the hips. For the CMJs, SJs, and DJs each jump modality started with three submaximal attempts, followed by three maximal attempts. The break between each jump varied between 30 s and 3 min (longer breaks between maximal attempts). Additional jumps were performed if any of the systems failed to measure the jump, if the software from the portable systems did not approve the jump, or if the participants failed to land on the portable systems.

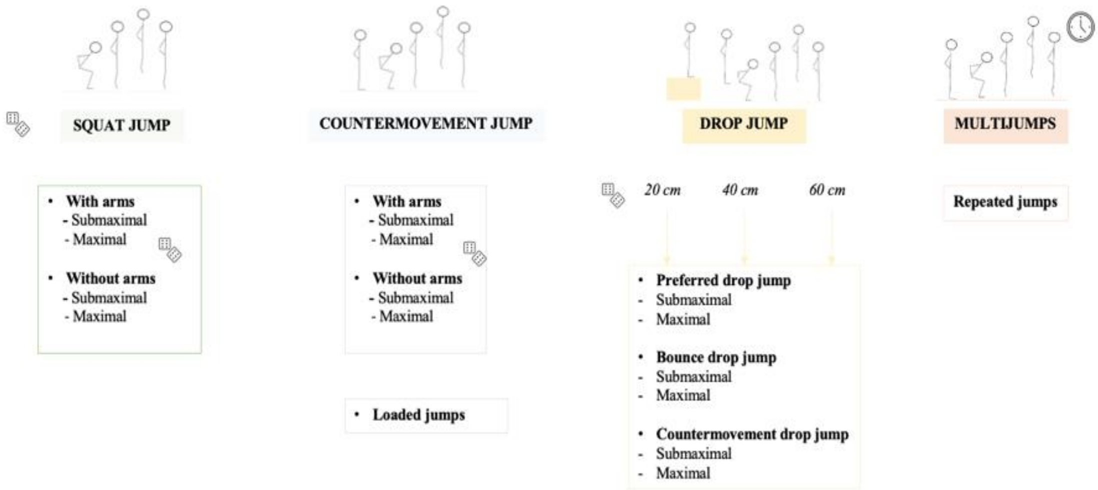

Figure 2. *An illustration of the jump protocol applied in this project. : randomized order. Please see the text for further information. Own illustration made in Microsoft® PowerPoint, v. 16.54 (Microsoft 365, Microsoft Corporation).*

For the submaximal attempts, the participants were instructed to aim for approximately 40%, 60%, and 80% of the perceived maximal jump height. For maximal attempts, the participants were instructed to aim for maximal jump heights. For the jumps excluding the arms, the hands were placed on the hips. For the jumps including the arms (CMJs and SJs), the participants were free to choose how they wanted to use their arms, as long as the jump was approved by the software (e.g., SJ still needed to be performed without a preliminary countermovement).

2.4.1 Countermovement Jumps

Each jump was performed on "jump" following the commands of "3-2-1-jump". The CMJs were performed with a self-selected depth of the countermovement. For the participants that tended to lift their CoM prior to the countermovement, extra instructions were given to stand completely still before initiating the jump. The exclusion criteria were based on the results from the software—i.e., if the software approved the jump as a CMJ it was kept for further analysis.

2.4.2 Squat Jumps

The participants were instructed to descend to a squat position on the counts of 2 following the commands of "3-2-1-jump", and to jump on the commands of "jump". The primary instructions were to jump without performing a preliminary countermovement. No instructions were given to the depth of the squat position—however, the participants who struggled excluding a preliminary countermovement tended to be more upraised. For these participants, instructions were given to aim for approximately 90° in the knee joint when in squat position. Additionally, some participants tended to have movement in the squat position, though not performing a countermovement. These participants were encouraged to achieve a more stable squat position. The mentioned instructions were deemed important as the squat position is a phase of the movement from where body weight can be extracted, and where integration of the GRF-time data is initiated (using forward integration procedures). The exclusion criteria were based on the results from the software—i.e., if the software approved the jump as a SJ it was kept for further analysis.

2.4.3 Drop Jumps

The DJs were performed from three box heights: 20, 40, and 60 cm. Please note that the exact drop height was slightly lower, due to the height of each portable force platform (Table 1). The order of the drop height was randomized for each participant. At each drop height, the participants performed three submaximal and three maximal jump height attempts. Furthermore, the participants were given three specific drop landing instructions (one instruction per drop height). Regardless of the drop height, the instructions were given in the following order: a preferred drop, a bounce drop, and a countermovement drop. For the preferred drop, no specific drop instructions were given. For the bounce drop, the participants were instructed to land from the box and push off with as short a contact time as possible. For the countermovement drop, the participants were instructed to land from the box with a countermovement. The participants were instructed to drop on “drop” following the commands of “3-2-1-drop”, and then jump for submaximal or maximal heights. The primary exclusion criteria were based on the results from the software—i.e., if the software approved the jump as a DJ it was kept for further analysis. A secondary exclusion criterion was made if the participants did not successfully land on the portable force platform (as we used backward integration procedures for DJ calculations; see *Data Analysis*).

For the included jumps in this study, the participants were instructed to stand upraised and completely still before the jump/drop (for CMJs and DJs: on the counts of 3, 2, 1; for the SJs: on the counts of 3). The participants were instructed to land on the portable force platform and to come to an upraised standing position, remaining still for at least 1 s until given instructions to step off. In the standing still positions the arms were placed down to the side (when jumps were performed with arms) or on the hips (when jumps were performed without arms). In many cases, especially for the maximal jump height attempts, the participants struggled to land on the portable force platform and reach a still position. In that case, instructions were given to step back on the portable system and come to a standing still position, as quickly as possible (except for DJs; see explanation above). Stepping back on the force platform was an instruction given as we wished to compare body weight extracted from the beginning of the jump, versus the end.

The jump protocol was performed on one combination of force platform comparisons (e.g., Kistler system on top of reference system). Most of the participants (n = 21) performed the jump protocol twice, thus including two different force platform combinations on the same day. To ensure a similar range across all force platform devices, which force platform combination was used for the first jump protocol was randomized between participants. Ten of the participants performed the jump protocol on more than one occasion (i.e., two or more test days). The number of jumps performed in one jump protocol varied between approximately 45 and 60 jumps.

2.5 Static Test Procedures

The purpose of the loading and unloading procedure was to obtain a measure of the linearity qualities of each of the force platforms included in this study. Moreover, we wished to examine how accurately the included force platforms measured static weights of known loads.

The procedure involved placing known loads (Eleiko, Sweden) of 0 to 325 kg, in the center of each of the included force platforms. The loads were placed in the following order for the loading conditions: 6 loads of 20 kg, 2 loads of 10 kg, 4 loads of 15 kg, 5 loads of 25 kg, and removed in the reversed order. The loads were placed/removed from the force platforms in 5 s intervals, and each loading condition was measured for 3 s. A zero-measure was taken as the first and final measure, resulting in 36 measures for this test.

2.6 Data Analysis

All data was analyzed in MATLAB (R2021b version; Math-Works, Inc, Natick, MA).

In total (across all devices, participants, and jump modalities), 3378 jumps were performed over a large range of jump heights (~ 9 to 72 cm). Due to challenges matching the files for the same jump, 316 jumps were excluded, leaving 3062 jumps included for further analyses. Of these 873 CMJs, 881 SJs, and 1202 DJs were included in this study. Due to challenges extracting and matching results from the software to those of the GRF-time data, 392 jumps were excluded from the analyses. From there, a total of 32 jumps were excluded based on criteria set in our calculation code (explanation given below). Next, of the included jumps, 103 outliers were excluded from the Hardware analysis (see explanation below) based on the generalized extreme Studentized deviate test, where one outlier was removed per iteration based on hypothesis testing. After removing these outliers, using the same approach, 71 outliers were excluded from the Software analysis. We choose to remove outliers as some extreme outliers (> 80 cm difference in jump height) were present, which could not be explained systematically. That is, these outliers were not all due to large differences in body weight, take-off velocity, or faulty integration starts. We visually checked the GRF-time curves for these outliers, and they revealed no apparent reasons for these to become outliers during the calculation procedure. After removing all outliers, through the processes explained above, a total of 677 CMJs, 678 SJs, and 998 DJs, were analyzed through the procedures explained in the forthcoming paragraphs.

For the purpose of this study, the kinematic data were analyzed for 14 participants, resulting in 1426 jumps included in the CoM analysis. Of the included jumps, 42 were excluded based on the outlier test explained above. After removing all outliers, 414 CMJs, 412 SJs, and 600 DJs were analyzed in this paper.

Please see Figure 3 for an overview of the analyzed data. For the purpose of this study, only jump height was analyzed. First, the raw GRF-time data obtained from both force platform systems concurrently were extracted and analyzed through the same algorithm (follow trace 1 in Figure 3). These comparisons were included to exclude any influence of differences in calculation procedures and will be referred to as Hardware analysis. Next, we extracted the GRF-time data from each of the portable systems and compared the calculation of the GRF-time data from the Hardware analysis (set as a reference calculation), with jump height measured from the proprietary software (follow trace 2 in Figure 3). These comparisons will be referred to as Software analysis. Furthermore, jump height from the whole-body CoM trajectory was compared to the reference calculation obtained from the reference force platform, and the calculations from each proprietary software (follow trace 3 in Figure 3). These comparisons will be referred to as CoM analysis. The static trials were analyzed separately from the jump data.

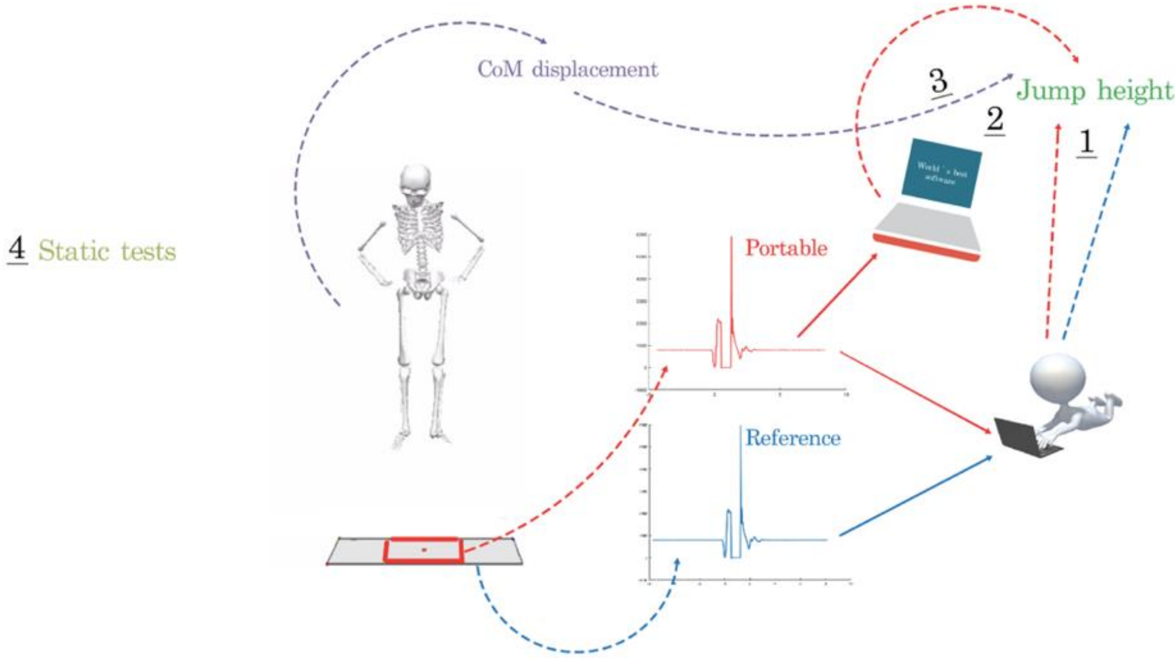

Figure 3. *An illustration of the experimental approach applied in this study. The grey rectangle represents the reference force platform. The red rectangle on top represents a portable force platform. Blue graph: ground reaction forces (GRF) from the reference force platform, red graph: GRFs from the portable force platform. Trace 1: the GRF measured concurrently were extracted from the reference and portable system and jump height was calculated through the same algorithm. Trace 2: the GRF from the portable force platform (red graph) was calculated through the reference calculation (from trace 1), and the proprietary software calculation (computer) to obtain jump height. Trace 3: the maximum displacement of the whole-body CoM obtained from 3D motion capture (jumper) was compared to the reference calculation from trace 1, and the proprietary software calculations from trace 2. Trace 4: static testing was conducted to supplement the results from trace 1. The jumper is an example from one of the participants, taken from the work of constructing the model in Visual 3D (Visual 3D, C-Motion Inc., Rockville, MD, United States). Own illustration made in Focusky v.3.7.7. (Focusky Software Co., Ltg, Hong Kong).*

2.6.1 Hardware Analysis

The GRF-time data was extracted from each of the force platform systems without manipulation and will be referred to as raw data as it was not resampled nor filtered before analysis, although some of the portable force platform systems reported their data to be filtered (Table 1).

Jump height was calculated using the impulse-momentum theorem by extracting the velocity at take-off, which was then used to calculate jump height through the following equation:

$$jump\ height = \frac{v^2}{2g} \tag{1}$$

where v = velocity of the CoM at take-off, and g = 9.81m·s^{-2}.

As a result of the set-up (one force platform on top of another) and possible noise in the GRF-time signal, we choose to correct the GRF-time data for an offset value. This was done for both force platform systems (in-ground and portable). The offset was defined as the average force over 0.05 s, in a period corresponding to the middle of the flight phase (all flight phases were > 0.05 s). The middle of the flight phase was determined by finding the minima in a low-pass filtered copy of the force measurement (second-order, bidirectional, Butterworth low-pass filter with a cutoff frequency of 2 Hz). The offset value was then extracted from the entire GRF-time series.

Next, body weight was extracted by averaging the GRF-time data over a 1 s period, as recommended by Street et al. (2001). We choose to extract body weight from the end of the jump (when the person was standing still), even though we acknowledge that most studies report body weight averaging periods taken prior to the jump (for CMJs and SJs). The approach of averaging body weight from the end of the jump for CMJs and SJs was chosen mainly since not all software of the portable systems enabled us to extract a sufficient amount of data from the beginning of the jump to follow the recommendation of body weight averaging periods ≥ 1 s. The body weight averaging period (1 s) was initiated at the time point in which the ratio of a moving standard deviation and moving average of the force, taken from landing until the end of the capture, reached a minimum. Body mass was calculated by dividing body weight by 9.81m·s^{-2}.

For the CMJs and SJs, the start of movement was defined as the first timeframe in which the GRF-time data was below (CMJ) or above (SJ) a threshold of five percent of body weight, as recommended by several authors (Owen et al., 2014; Pérez-Castilla et al., 2019; Donahue et al., 2021). If the start of movement occurred at a time point that was < 0.25 s after the start of recording, jump height was not calculated. This was to ensure that the participants were in a quiet standing position when the recording started.

The GRF-time data were integrated using the trapezoid rule as this is the most reported integration method, showing acceptable accuracy, in the literature with regards to jump height calculations (Street et al., 2001; Moir et al., 2009; Dias et al., 2011; Nielsen et al., 2019; McMahon et al., 2021; Wade et al., 2022). For the CMJs and SJs, the start of integration was set as the first time point in which the standard deviation of the GRF-time data, between the start of the capture and the start of movement (see explanation above), reached ≤ 0.01. Hence, we applied a forward integration procedure. For the DJs, the start of integration was set as the first time point in which the standard deviation of the GRF-time data, between landing (see explanation below) and the end of the capture, reached ≤ 0.01. Hence, for DJs, we applied a backward integration procedure. If the standard deviation of the GRF-time data in the defined period failed to reach ≤ 0.01, jump height was not calculated. The ≤ 0.01 standard deviation method was chosen to ensure an acceptable integration start (with minimum noise) for all the included GRF-time data—that is, for jumps performed with and without the use of arms, as well as submaximal and maximal jump height attempts. Simply setting the start of integration to a predefined point before the start of the movement, as previous studies have suggested (Street et al., 2001; Meylan et al., 2011; Owen et al., 2014), led in some instances to an unstable integration start for the included jump modalities in this study. The threshold of ≤ 0.01 was chosen as it was the threshold where we could ensure an acceptable integration start for the included jumps in this study.

Landing was determined as the first time point in which the GRF-time data reached a threshold ≥ 10 N, in a time frame between the middle of the flight phase and the end of the capture.

Take-off was determined as the first time point at which the GRF-time data reached a threshold ≤ 10 N, in a time frame between the peak force prior to take-off, until the middle of the flight phase. We aimed to apply the take-off thresholds that have been used and/or recommended in the literature—e.g., the last force value before flight phase which reaches a threshold of mean GRF during flight phase plus five standard deviations (Pérez-Castilla et al., 2021). The reason why the commonly used take-off thresholds did not fit all our data was simply that some of the portable force platform systems applied a filter to their data, and the differences in sampling frequencies were in some cases large (200 vs. 2000 Hz). We also believe our setup (a portable system placed on top of the reference system) created larger noise in the data at the point of take-off, making it more challenging to find a robust take-off threshold for the included jumps in this study.

Acceleration was obtained by subtracting body weight from the GRF-time data, between the start of integration and take-off (for CMJs and SJs) or landing (for DJs), and then normalizing this period of GRF-time data to body mass. Velocity was obtained by integrating the acceleration over time. The velocity at take-off (for CMJs and SJs) or landing (for DJs) was then extracted and used to calculate jump height according to Equation 1.

2.6.2 Software Analysis

The GRF-time data from the portable systems were handled as explained for the Hardware analysis. The results from the proprietary software were extracted and carefully matched with the GRF-time data from the portable force platform systems. The jump heights obtained from the Hardware analysis and the jump heights obtained from the proprietary software calculations were then compared statistically as explained below. Please see Table 2 for information on the calculation procedures for the included software. For all jump modalities and software (except for ForceDecks), jump height was calculated through Equation 1.

The ForceDecks system offered several equation options for jump height calculations, and for the SJs we choose to extract jump height calculated as the difference between the maximum displacement of the CoM and the position of the CoM at take-off, obtained by double integrating the GRF-time curve. For DJs, the ForceDecks system calculated jump height only from the flight-time method (see example in Baca (1999) and Linthorne (2001)). CMJ heights were calculated through Equation 1.

The Kistler, ForceDecks, and HurLabs systems offered several options for the data processing steps shown in Table 2, where the information given in Table 2 were the default values in these software programs.

Table 2. *Proprietary software calculation information.*

Software	Kistler	ForceDecks	MuscleLab	HurLabs
Averaging periods of BW (s)	–	1	–	–
Start of movement	10 N	20 N	–	–
Method of integration	–	Trapezoid	–	–
Start of integration	–	Start of movement	–	–
Take-off threshold (N)	10	20	–	5
Sampling frequency (Hz)	1000	1000	200	1200
Filter	No	No	–	Yes

Abbreviations: BW, body weight; N, newton; H, hertz; s, seconds; –, information not known.

2.6.3 CoM Analysis

Marker locations were registered in a static trial in order to determine the static calibration of the kinematic model. The kinematic model used in this study was a modified version of the model applied by Eriksrud et al. (2022), and was constructed in Visual 3D (Visual 3D, C-Motion Inc., Rockville, MD, United States). The CoM was extracted from Visual 3D, where they report that the segmental parameters stem from the Dempster study (1955). CoM data was filtered using a second-order, bidirectional, Butterworth low-pass filter with a cutoff frequency of 20 Hz.

Jump height was calculated as the difference between the maximum CoM displacement whilst the participants were in the air and the CoM displacement at take-off (for CMJs and SJs), or landing (DJs). Take-off and landing were defined according to the definitions of the force data as explained above.

2.6.4 Static Analysis

For each of the 36 loading conditions, the mean values were extracted through a customized script in MATLAB (R2021b version; Math-Works, Inc, Natick, MA). The mean values of the measured force were then compared against the known weights. Linearity was calculated as the Pearson product-moment correlation. The difference between the known and measured weights, and those of the loading and unloading conditions, were analyzed. Note that the results from the HurLabs system were not analyzed in this study, due to challenges in extracting the data from the computer.

2.7 Statistical Analysis

Statistical analyses were performed in MATLAB (R2021b version; Math-Works, Inc, Natick, MA). Confidence limits (CL) for all analyses were set at 95%. Alpha levels for significance testing were set at 5%.

For the main analysis, all jumps (submaximal and maximal attempts, with and without arms (SJs and CMJs), and from the three drop heights (DJs)), were grouped. Note that attempts with or without arms, and from all three drop heights, are highlighted in the graphical representations of the results.

Mean, 95% CL, and standard deviation (SD) of all differences were calculated and are presented graphically as Bland-Altman plots (Bland & Altman, 1999). The differences were defined as follows:

- Hardware analysis: portable force platform – reference force platform.
- Software analysis: proprietary software calculation – reference calculation.
- CoM analysis: CoM jump height – reference calculation, and proprietary software calculation – CoM jump height.
- Static trials: portable force platform – reference force platform.

These definitions are according to the definition by Hopkins (2017), and are presented in absolute and relative terms (relative to the portable/alternative system). The probability of difference between the portable and reference systems was evaluated through a paired sample *t*-test. Typical error of estimate (TEE) was calculated in absolute and relative terms, according to the definition by Hopkins (2017).

A one-way analysis of ANOVA was performed to examine differences between force platform systems for the Hardware and Software analyses, for all jump modalities. The input for the ANOVA for each force platform system was the difference between the respective portable force platform and the reference force platform (Hardware), or the difference between the proprietary software and the reference calculation (Software). The one-way analysis of ANOVA revealed that there was a statistically significant difference between at least two force platform systems for all jump modalities, for both the Hardware and Software analyses (Table 3). A multiple comparison analysis, using the Tukey-

Kramers post hoc test, was performed to reveal which of the force platform systems differed from one another.

__Table 3.__ Results from the one-way ANOVA for the Hardware and Software analyses for each jump modality.

Analysis	Jump type	Between-group df	Within-group df	F-value	*p*-value
Hardware	*CMJ*	3	673	27	<0.001
	SJ	3	673	36	<0.001
	DJ	3	994	108	<0.001
Software	*CMJ*	3	673	66	<0.001
	SJ	3	674	204	<0.001
	DJ	3	934	65	<0.001

Abbreviations: CMJ, countermovement jump; SJ, squat jump; DJ, drop jump; df, degrees of freedom; *p*, probability.

The average difference between force platform systems was calculated as follows:

$$\frac{mean_{port}1 + mean_{port}2}{2} \tag{2}$$

where $mean_{port}1$ represents the average difference between one portable force platform and the reference, whilst $mean_{port}2$ represents the same difference for another portable force platform system.

The pooled standard deviation of the differences between force platforms was calculated as follows:

$$\frac{\sqrt{std_{port}1^2 + std_{port}2^2}}{2} \tag{3}$$

where $std_{port}1$ represents the standard deviation of $mean_{port}1$, whilst $std_{port}2$ represents the standard deviation of $mean_{port}2$.

Results

3.1 Hardware Analysis

The difference between the portable and reference force platforms was significant at a level of $p \leq 0.001$, for all force platform systems, except for CMJ heights measured by MuscleLab (p = 0.77). For all jump modalities, the systematic difference ranged from −1.0

to 1.4 cm, and in relative terms from −2.9% to 3.8%. The TEE ranged from 0.4 to 1.8 cm in absolute terms, and from 1.1% to 5.0% in relative terms (Table 4).

3.1.1 Countermovement Jumps

ForceDecks and HurLabs on average underestimated CMJ heights, while Kistler overestimated CMJ heights compared with the reference force platform (Figures 4 and 7). MuscleLab did not differ on average from the reference force platform for CMJ height measures. The differences between force platform systems were significant for all systems at a level of $p < 0.001$, except between ForceDecks and HurLabs ($p = 0.37$) (Table 5).

3.1.2 Squat Jumps

All force platform systems on average underestimated SJ heights, except for Kistler which overestimated SJ heights compared with the reference force platform (Figures 5 and 8). The differences between force platform systems were significant at a level of $p < 0.001$, between Kistler and all other force platform systems, and between ForceDecks and MuscleLab. The difference between MuscleLab and HurLabs was significant at a level of $p < 0.05$. No significant difference was observed between ForceDecks and HurLabs ($p = 0.57$) (Table 5).

3.1.3 Drop Jumps

Kistler and MuscleLab on average overestimated DJ heights, whilst ForceDecks and HurLabs underestimated DJ heights, compared with the reference force platform (Figures 6 and 9). The differences between force platform systems were significant for all systems at a level of $p < 0.001$ (Table 5).

3.2 Software Analysis

The difference between the proprietary software and reference calculation was significant at a level of $p < 0.001$, for all force platform systems. For all jump modalities, the systematic difference ranged from −3.6 to 4.2 cm in absolute terms, and from −11.6% to 11.1% in relative terms. The TEE ranged from 1.2 to 6.9 cm in absolute terms, and from 3.2% to 22.3% in relative terms (Table 4).

3.2.1 Countermovement Jumps

Kistler and ForceDecks on average underestimated CMJ heights, while MuscleLab and HurLabs overestimated CMJ heights compared with the reference calculation (Figures 4 and 7). The differences between software were significant for all systems at a level of $p < 0.001$, except between Kistler and ForceDecks ($p = 0.96$) (Table 5).

3.2.2 Squat Jumps

All proprietary software on average overestimated SJ heights compared with the reference calculation (Figures 5 and 8). HurLabs exhibited significant differences with all other systems at a level of $p < 0.001$. Kistler, ForceDecks, and MuscleLab were not significantly different from each other (Kistler vs. ForceDecks: $p = 0.30$, Kistler vs. MuscleLab: $p = 0.47$, ForceDecks vs. MuscleLab: $p = 0.97$) (Table 5).

3.2.3 Drop Jumps

All proprietary software on average underestimated DJ heights, except for MuscleLab which slightly overestimated DJ heights compared with the reference calculation (Figures 6 and 9). The differences between force platform systems were significant at a level of $p < 0.001$, except between Kistler and ForceDecks which differed from each other significantly at a level of $p < 0.01$. No significant difference was observed between ForceDecks and HurLabs ($p = 0.75$) (Table 5).

3.3 CoM Analysis

The CoM model overestimated jump height by on average 0.9 cm for the CMJs, and 0.6 cm for the SJs, while DJs were underestimated by on average 0.6 cm compared with the reference calculation (Figure 10).

For CMJs and SJs, the proprietary software calculations from the Kistler and HurLabs systems on average overestimated jump heights, whilst the ForceDecks and MuscleLab calculations underestimated jump heights compared with the CoM model (CMJs: Figure 11, SJs: Figure 12). For DJs, the proprietary software calculation from the MuscleLab system on average overestimated jump height, whilst the Kistler, ForceDecks, and HurLabs calculations underestimated jump heights compared with the CoM model (Figure 13).

3.4 Static Analysis

The linearity for all included force platforms, for the loading versus unloading conditions, was on average r = 1.00. The difference between known and measured weights in the loading and unloading conditions ranged from –2.6 to 14.1 N for all force platform systems (Table 6), where all strain gauge force platforms on average overestimated the measured force, while the piezoelectric force platform slightly underestimated the measured force (Figure 14).

Table 4. *Measures of agreement between the portable systems and reference system for countermovement jump, squat jump, and drop jump heights, in the Hardware and Software analyses.*

Analysis	Jump type	Force plate	*n*	Mean ± SD (cm) (R)	Mean ± SD (cm) (P)	Mean difference ± SD (cm) (P – R)	Mean difference ± SD (%)	TEE ± CL (cm)	TEE ± CL (%)
Hardware	CMJ height (cm)	*Kistler*	151	37.2 ± 10.8	38.5 ± 10.8	1.4 ± 1.0***	3.6 ± 2.5	1.0 ± 0.7	2.5 ± 1.7
		ForceDecks	163	36.2 ± 9.3	35.6 ± 8.9	–0.7 ± 0.8***	–1.9 ± 2.1	0.7 ± 0.4	1.9 ± 1.2
		MuscleLab	186	35.2 ± 8.4	35.3 ± 8.9	0.0 ± 1.8	0.1 ± 5.2	1.8 ± 1.2	5.0 ± 3.3
		HurLabs	177	35.8 ± 8.4	35.4 ± 8.3	–0.5 ± 0.7***	–1.4 ± 2.0	0.7 ± 0.5	2.0 ± 1.4
	SJ height (cm)	*Kistler*	174	34.7 ± 10.5	35.9 ± 10.8	1.2 ± 0.7***	3.4 ± 1.9	0.6 ± 0.4	1.7 ± 1.1
		ForceDecks	122	36.3 ± 9.7	35.7 ± 9.5	–0.6 ± 0.6***	–1.7 ± 1.6	0.5 ± 0.4	1.4 ± 1.1
		MuscleLab	188	33.8 ± 8.7	33.5 ± 8.7	–0.3 ± 0.8***	–1.0 ± 2.4	0.8 ± 0.5	2.4 ± 1.6
		HurLabs	194	34.3 ± 8.5	33.8 ± 8.3	–0.5 ± 0.4***	–1.5 ± 1.2	0.4 ± 0.2	1.1 ± 0.7
	DJ height (cm)	*Kistler*	246	33.3 ± 11.1	34.6 ± 11.3	1.3 ± 0.9***	3.8 ± 2.5	0.8 ± 0.5	2.3 ± 1.4
		ForceDecks	223	36.6 ± 11.5	36.3 ± 11.4	–0.3 ± 0.6***	–0.8 ± 1.6	0.6 ± 0.4	1.7 ± 1.1
		MuscleLab	292	34.3 ± 10.1	35.1 ± 10.5	0.8 ± 1.0***	2.3 ± 3.0	1.0 ± 0.6	2.8 ± 1.7
		HurLabs	237	35.4 ± 8.6	34.4 ± 8.3	–1.0 ± 0.7***	–2.9 ± 2.0	0.6 ± 0.4	1.7 ± 1.2
Software	CMJ height (cm)	*Kistler*	151	38.5 ± 10.8	37.8 ± 11.2	–0.6 ± 1.5***	–1.5 ± 4.0	1.5 ± 1.0	3.8 ± 2.6
		ForceDecks	163	35.8 ± 8.9	35.1 ± 8.9	–0.5 ± 1.2***	–1.3 ± 3.5	1.2 ± 0.8	3.2 ± 2.3
		MuscleLab	186	35.3 ± 8.9	36.2 ± 8.4	1.0 ± 1.9***	2.7 ± 5.2	1.9 ± 1.3	5.2 ± 3.6
		HurLabs	177	35.4 ± 8.3	38.0 ± 8.4	2.7 ± 1.9***	7.0 ± 5.1	1.9 ± 1.3	5.0 ± 4.5
	SJ height (cm)	*Kistler*	174	35.9 ± 10.7	36.8 ± 11.0	0.9 ± 1.8***	2.5 ± 4.8	1.7 ± 1.2	4.7 ± 3.1
		ForceDecks	122	35.7 ± 9.4	36.3 ± 9.4	0.6 ± 1.2***	1.6 ± 3.3	1.2 ± 0.8	3.3 ± 2.3
		MuscleLab	188	33.5 ± 8.7	34.1 ± 8.4	0.7 ± 1.7***	2.0 ± 5.1	1.7 ± 1.2	5.1 ± 3.3
		HurLabs	194	33.8 ± 8.3	38.0 ± 8.3	4.2 ± 1.7***	11.1 ± 4.6	1.7 ± 1.1	4.6 ± 3.0
	DJ height (cm)	*Kistler*	246	34.6 ± 11.4	31.0 ± 11.0	–3.6 ± 7.2***	–11.6 ± 23.1	6.9 ± 4.4	22.3 ± 14.2
		ForceDecks	223	36.3 ± 11.4	34.2 ± 9.7	–2.1 ± 2.6***	–6.1 ± 7.6	2.1 ± 1.4	6.1 ± 4.1
		MuscleLab	292	35.1 ± 10.5	35.3 ± 10.4	0.2 ± 1.2***	0.6 ± 3.4	1.2 ± 0.8	3.4 ± 2.3
		HurLabs	237	34.4 ± 8.4	32.7 ± 6.7	–1.7 ± 5.2***	–5.1 ± 16.0	5.2 ± 3.3	16.0 ± 10.1

Abbreviations: CMJ, countermovement jump; SJ, squat jump; DJ, drop jump; cm, centimeter; *n*, the number of jumps; SD, standard deviation; TEE, typical error of estimate; CL, 95% confidence limits; %, percentage; R, reference force platform (Hardware) and reference calculation (Software); P, portable force platform (Hardware) and proprietary software (Software). *Mean difference: $p < 0.05$. **Mean difference: $p < 0.01$. ***Mean difference: $p < 0.001$.

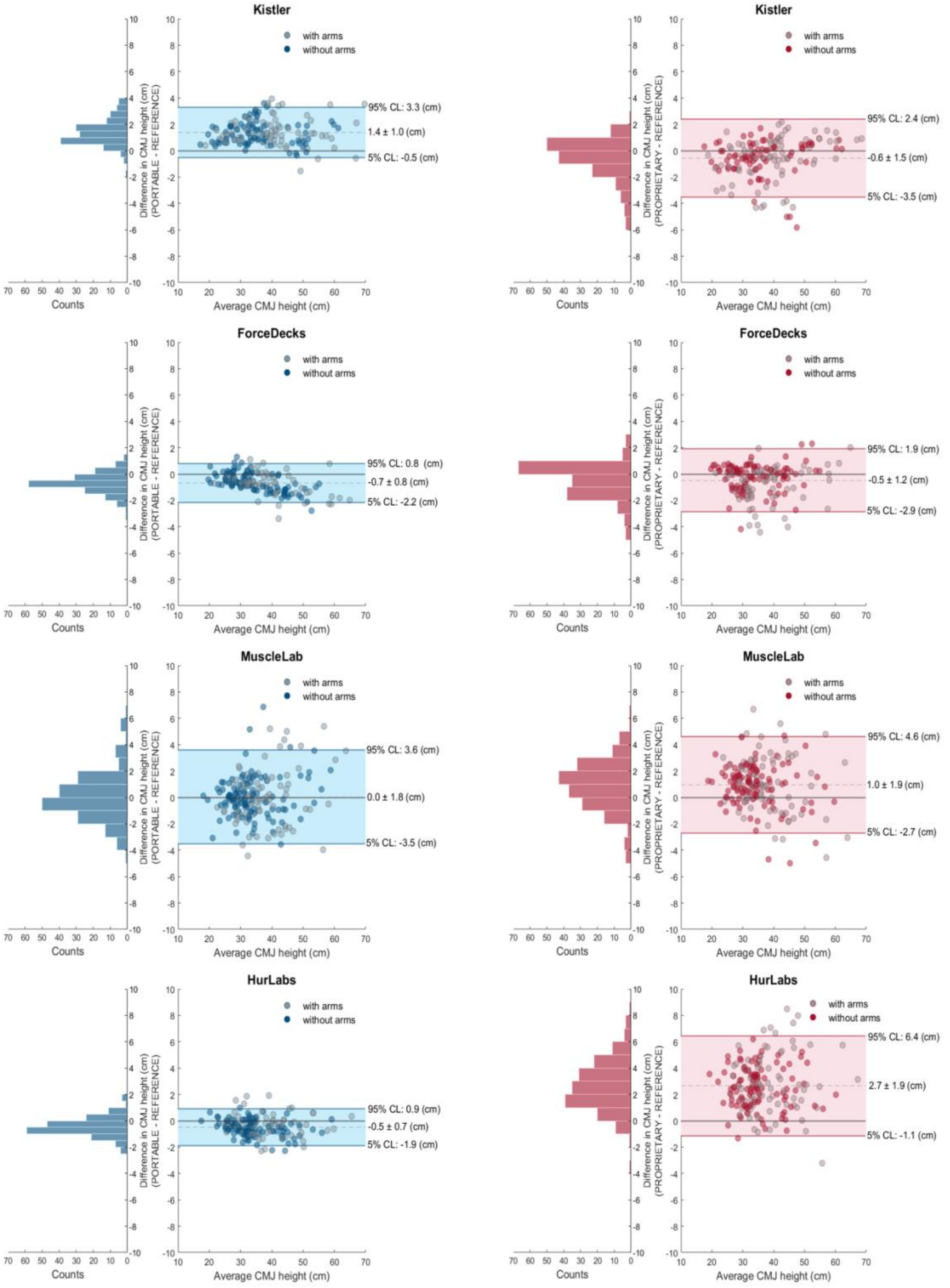

Figure 4. *The countermovement jump (CMJ). Blue graphs: Hardware analysis. Red graphs: Software analysis. The difference in CMJ height (cm) is plotted against the average CMJ height (cm) for each force platform system, as Bland-Altman (BA) plots (right graphs). The number of CMJs (counts) is plotted against the difference in CMJ height as histograms (left graphs). Hardware analysis: difference in jump height is defined as the portable force platform – reference force platform. Software analysis: difference in jump height is defined as the proprietary software calculation – reference calculation. BA plots: grey solid line = line of no difference, grey dotted line = mean difference, top line = 95% confidence limits (CL), bottom line = 5% CL. The values of the mean difference, 95% CL, and 5% CL are represented to the right of the BA plot. Grey dots: jumps performed with arm swing. Colored dots: jumps performed with arms on the hips. The jumps depicted are both submaximal and maximal CMJs.*

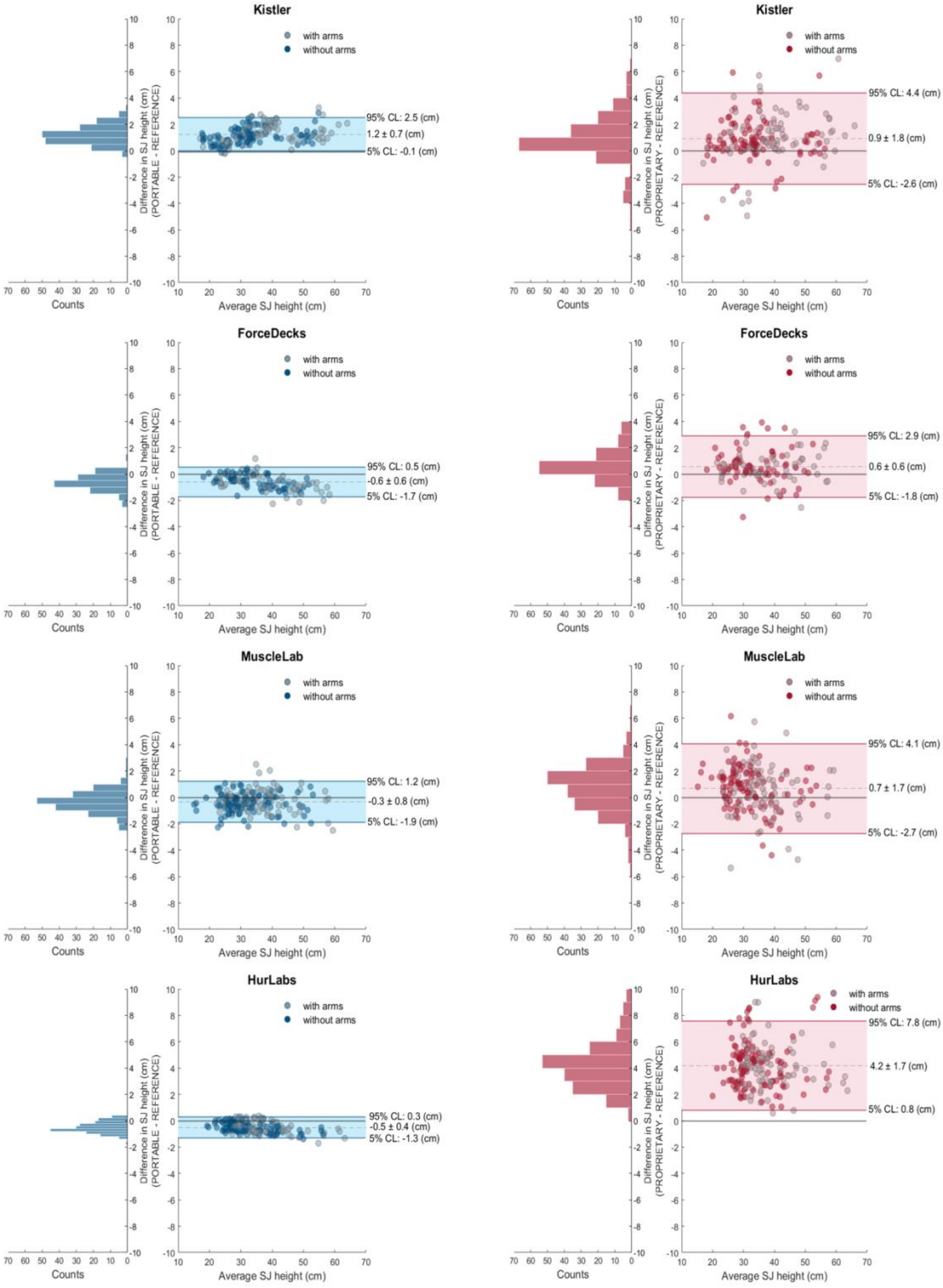

Figure 5. *The squat jump (SJ). Blue graphs: Hardware analysis. Red graphs: Software analysis. The difference in SJ height (cm) is plotted against the average SJ height (cm) for each force platform system, as Bland-Altman (BA) plots (right graphs). The number of SJs (counts) is plotted against the difference in SJ height as histograms (left graphs). Hardware analysis: difference in jump height is defined as the portable force platform – reference force platform. Software analysis: difference in jump height is defined as the proprietary software calculation – reference calculation. BA plots: grey solid line = line of no difference, grey dotted line = mean difference, top line = 95% confidence limits (CL), bottom line = 5% CL. The values of the mean difference, 95% CL, and 5% CL are represented to the right of the BA plot. Grey dots: jumps performed with arm swing. Colored dots: jumps performed with arms on the hips. The jumps depicted are both submaximal and maximal SJs.*

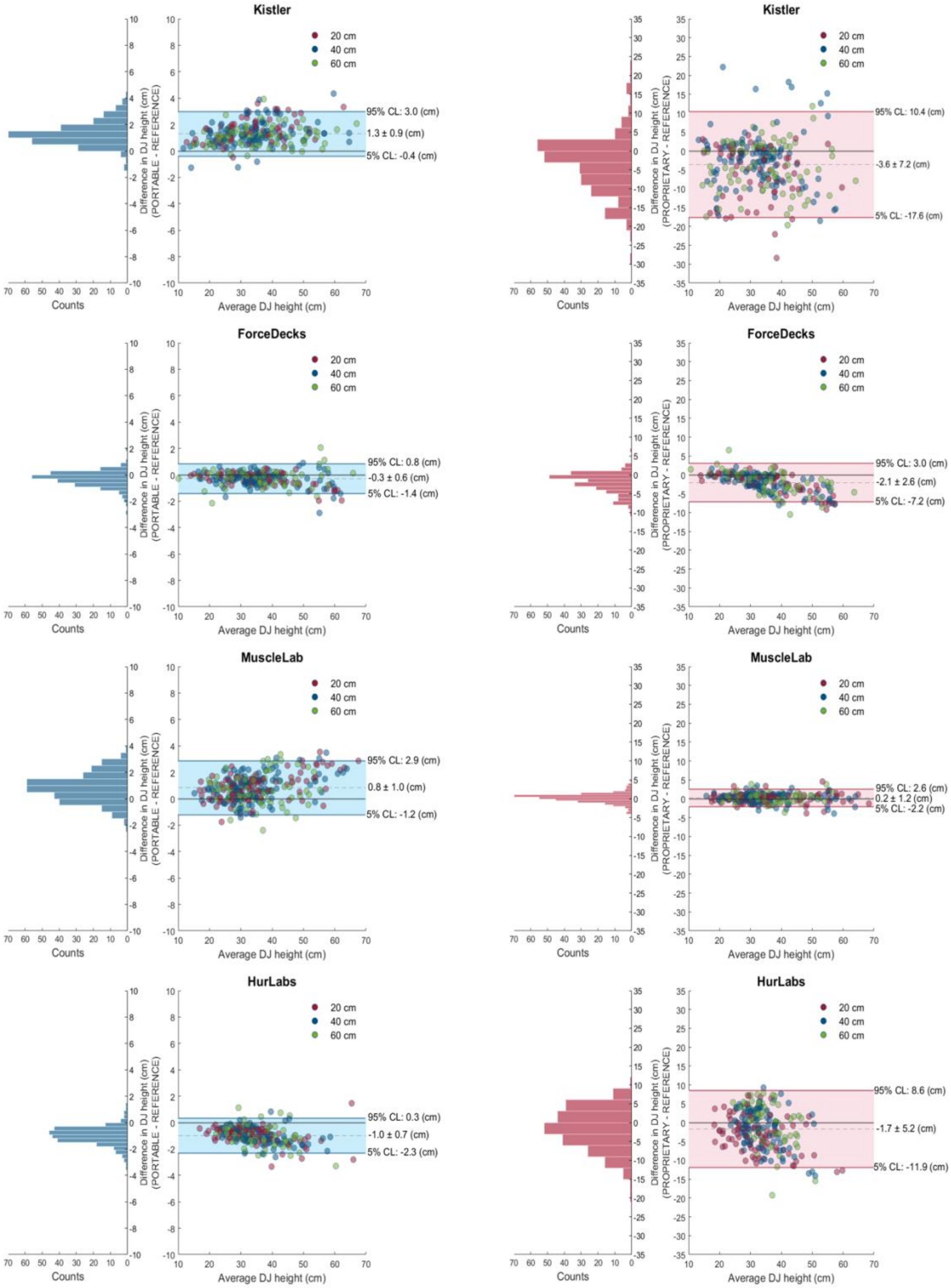

Figure 6. *The drop jump (DJ). Blue graphs: Hardware analysis. Red graphs: Software analysis. Note that the y-axis limits differ between the Hardware graphs and the Software graphs. The difference in DJ height (cm) is plotted against the average DJ height (cm) for each force platform system, as Bland-Altman (BA) plots (right graphs). The number of DJs (counts) is plotted against the difference in DJ height as histograms (left graphs). Hardware analysis: difference in jump height is defined as the portable force platform – reference force platform. Software analysis: difference in jump height is defined as the proprietary software calculation – reference calculation. BA plots: grey solid line = line of no difference, grey dotted line = mean difference, top line = 95% confidence limits (CL), bottom line = 5% CL. The values of the mean difference, 95% CL, and 5% CL are represented to the right of the BA plot. Red dots: jumps performed from a 20 cm box height. Blue dots: jumps performed from a 40 cm box height. Green dots: jumps performed from a 60 cm box height. The jumps depicted are both submaximal and maximal DJs.*

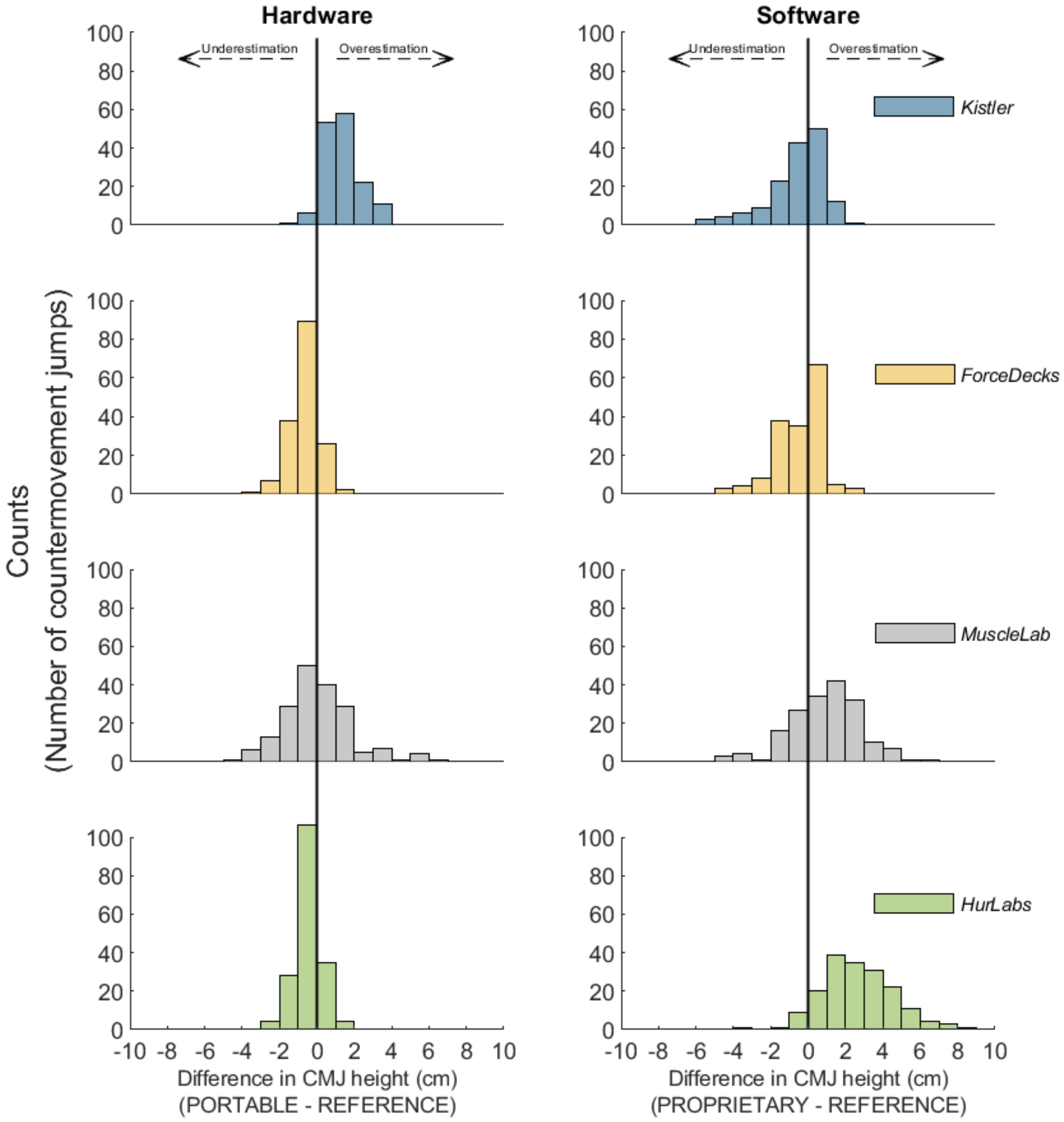

***Figure** 7. The number of countermovement jumps (CMJs) plotted against the difference in CMJ height (cm). The difference in jump height is defined as portable force platform – reference force platform for the Hardware analysis (left graphs), and as proprietary software calculation – reference calculation for the Software calculations (right graphs). Blue: Kistler, orange: ForceDecks, grey: MuscleLab, green: HurLabs. The black solid line extending from 0 difference in CMJ height represents the line of no difference. The arrows at the two top graphs denote whether there was an underestimation or overestimation in CMJ height compared with the set reference. Each histogram bar represents the number of CMJs where the difference in CMJ height falls within 1 cm.*

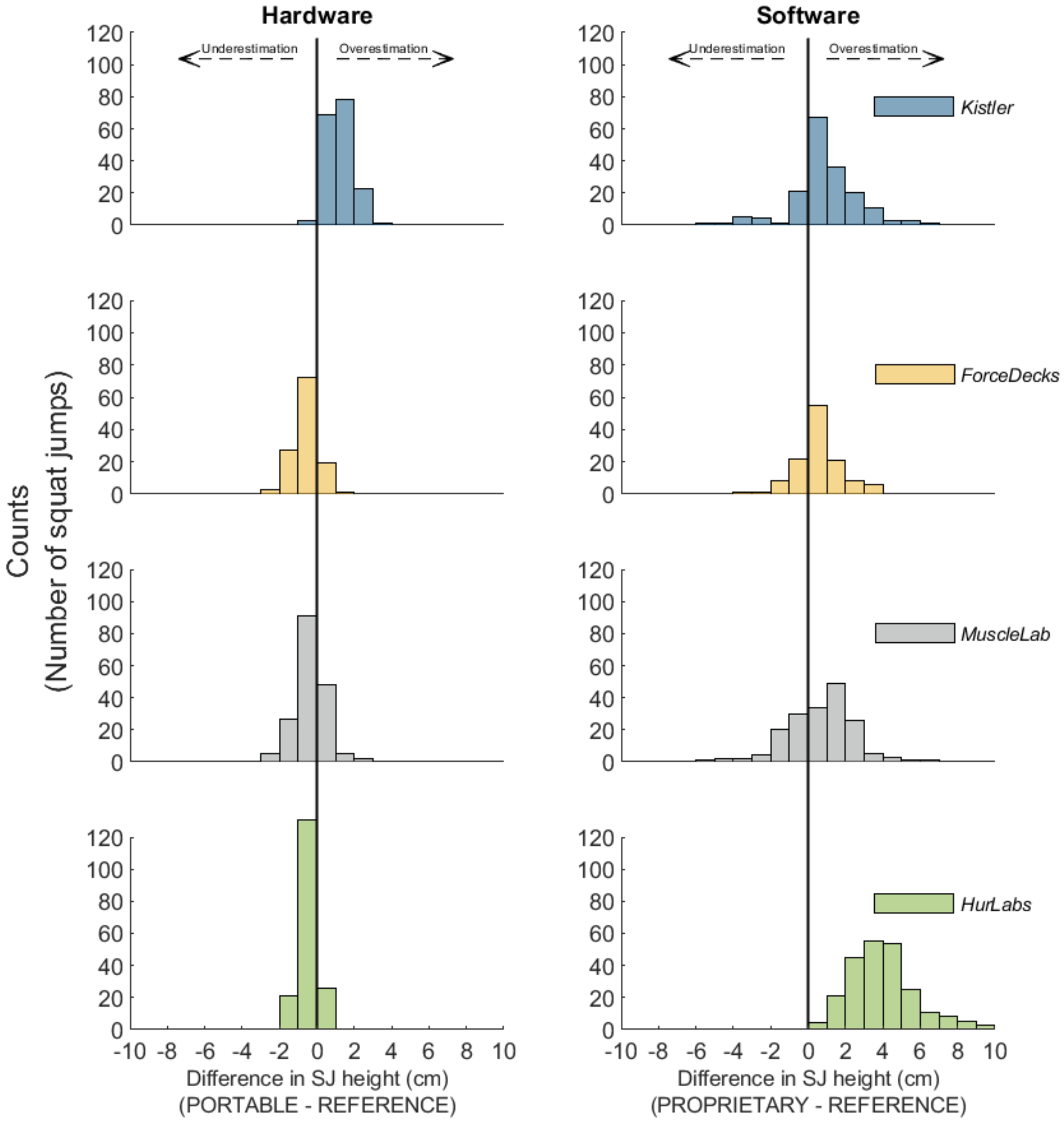

Figure 8. *The number of squat jumps (SJs) plotted against the difference in SJ height (cm). The difference in jump height is defined as portable force platform – reference force platform for the Hardware analysis (left graphs), and as proprietary software calculation – reference calculation for the Software calculations (right graphs). Blue: Kistler, orange: ForceDecks, grey: MuscleLab, green: HurLabs. The black solid line extending from 0 difference in SJ height represents the line of no difference. The arrows at the two top graphs denote whether there was an underestimation or overestimation in SJ height compared with the set reference. Each histogram bar represents the number of SJs where the difference in SJ height falls within 1 cm.*

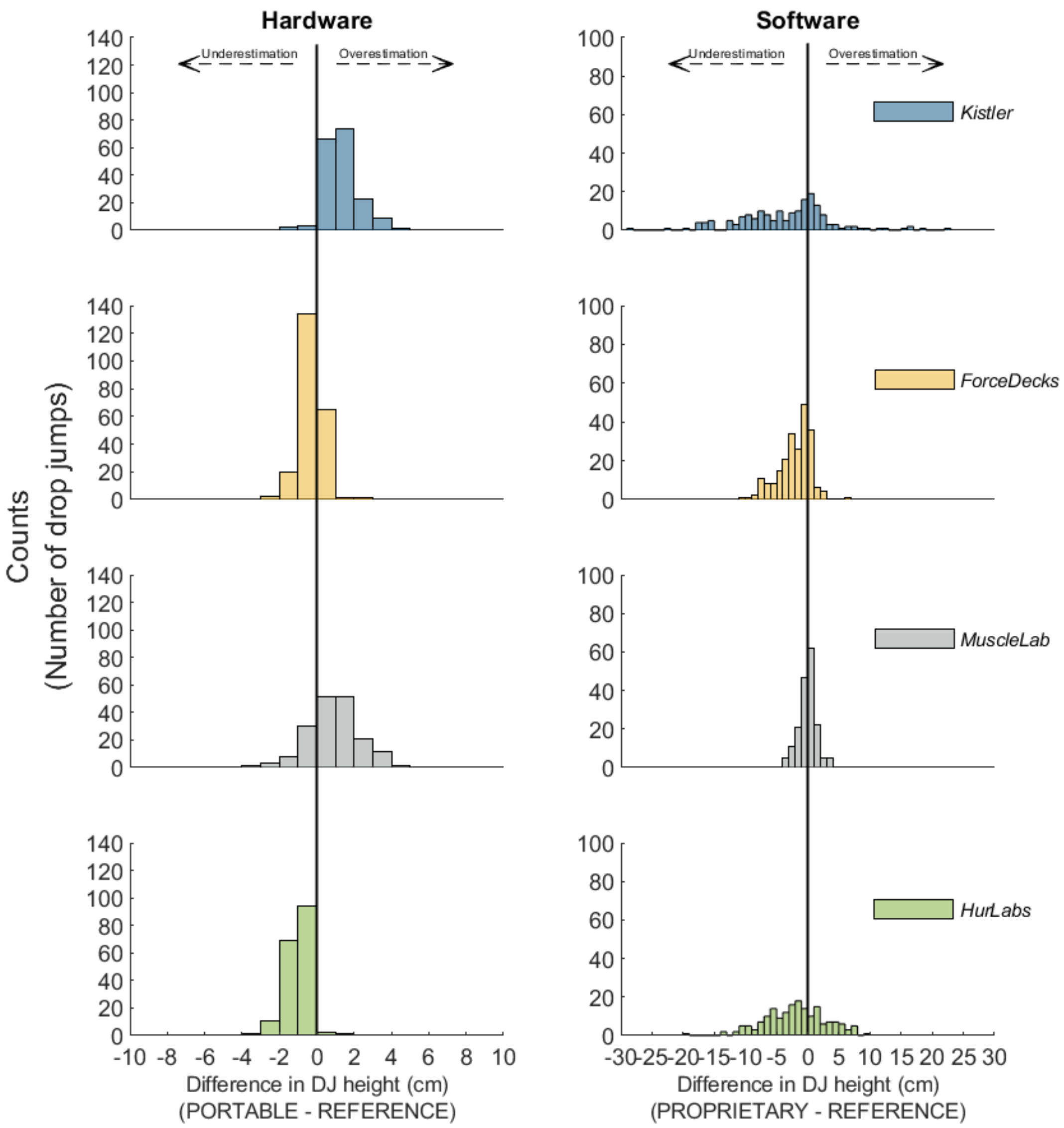

Figure 9*. The number of drop jumps (DJs) plotted against the difference in DJ height (cm). The difference in jump height is defined as portable force platform – reference force platform for the Hardware analysis (left graphs), and as proprietary software calculation – reference calculation for the Software calculations (right graphs). Note that the x- and y-axis limits differ between the Hardware graphs and the Software graphs. Blue: Kistler, orange: ForceDecks, grey: MuscleLab, green: HurLabs. The black solid line extending from 0 difference in DJ height represents the line of no difference. The arrows at the two top graphs denote whether there was an underestimation or overestimation in DJ height compared with the set reference. Each histogram bar represents the number of DJs where the difference in DJ height falls within 1 cm.*

Table 5. *Differences in countermovement jump, squat jump, and drop jump heights between the included force platform systems, for the Hardware and Software analyses.*

Jump type	**Force plate**	**Hardware**			**Software**		
		ForceDecks (cm)	*MuscleLab (cm)*	*HurLabs (cm)*	*ForceDecks (cm)*	*MuscleLab (cm)*	*HurLabs (cm)*
CMJ	*Kistler (cm)*	$2.1 \pm 0.6^{***}$	$1.4 \pm 1.0^{***}$	$1.9 \pm 0.6^{***}$	-0.1 ± 1.0	$-1.5 \pm 1.2^{***}$	$-3.2 \pm 1.2^{***}$
	ForceDecks (cm)		$-1.7 \pm 1.0^{***}$	-0.2 ± 0.5		$-1.4 \pm 1.1^{***}$	$-3.1 \pm 1.1^{***}$
	MuscleLab (cm)			$0.5 \pm 1.0^{***}$			$-1.7 \pm 1.3^{***}$
SJ	*Kistler (cm)*	$1.8 \pm 0.5^{***}$	$1.5 \pm 0.5^{***}$	$1.7 \pm 0.4^{***}$	0.3 ± 1.1	0.3 ± 1.2	$-3.3 \pm 1.2^{***}$
	ForceDecks (cm)		$-0.3 \pm 0.5^{***}$	-0.1 ± 0.4		-0.1 ± 1.0	$-3.6 \pm 1.0^{***}$
	MuscleLab (cm)			$0.2 \pm 0.4^{*}$			$-3.5 \pm 1.2^{***}$
DJ	*Kistler (cm)*	$1.6 \pm 0.5^{***}$	$0.5 \pm 0.5^{***}$	$2.3 \pm 0.6^{***}$	$-1.5 \pm 3.8^{**}$	$-3.8 \pm 3.7^{***}$	$-1.9 \pm 4.4^{***}$
	ForceDecks (cm)		$-1.1 \pm 0.6^{***}$	$0.7 \pm 0.5^{***}$		$-2.3 \pm 1.4^{***}$	-0.4 ± 2.9
	MuscleLab (cm)			$1.8 \pm 0.6^{***}$			$1.9 \pm 2.7^{***}$

Abbreviations: CMJ, countermovement jump; SJ, squat jump; DJ, drop jump; cm, centimeter. *Mean difference: $p < 0.05$. **Mean difference: $p < 0.01$. ***Mean difference: $p < 0.001$.

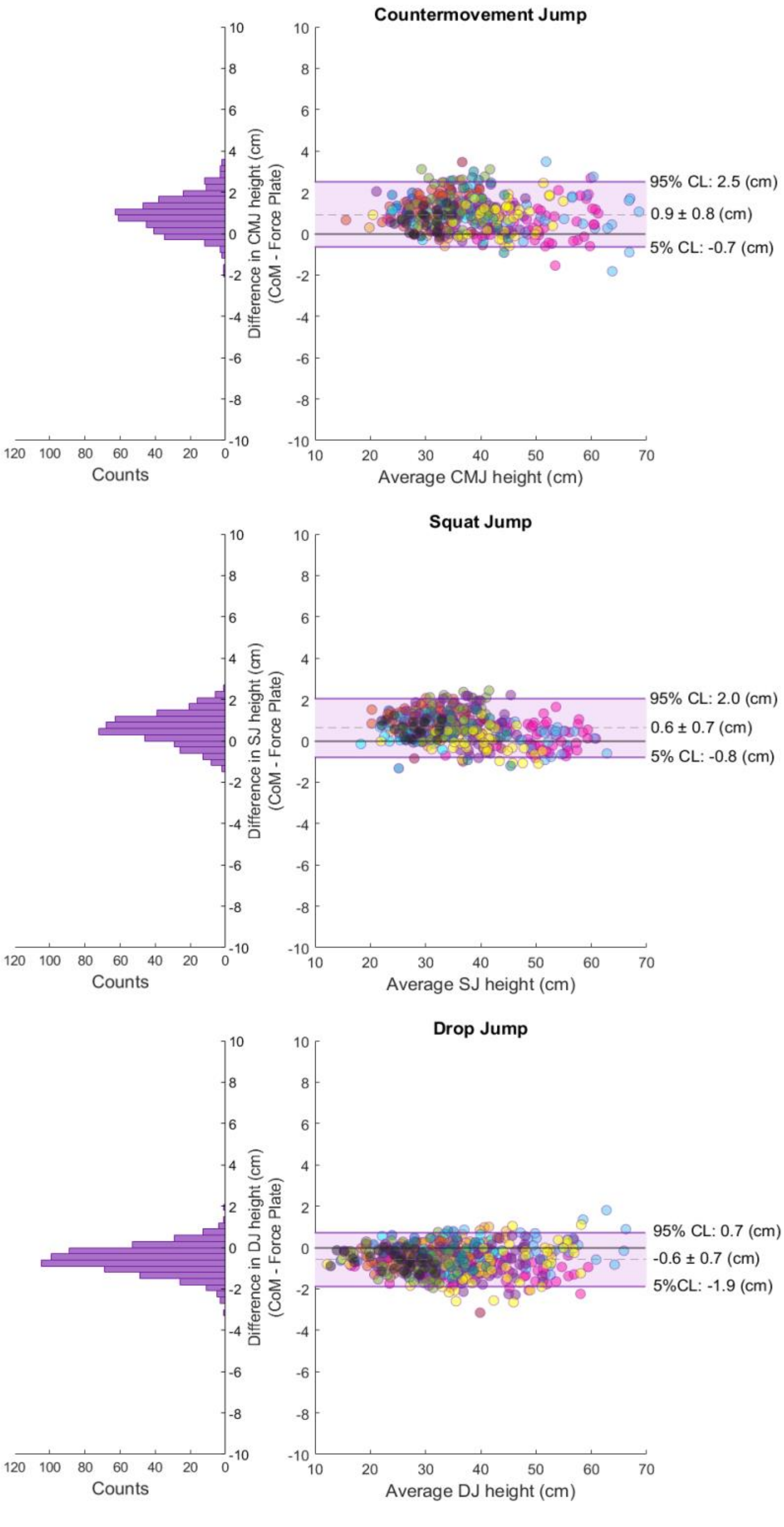

Figure 10. *Comparison between the center of mass (CoM) analysis and reference calculation from the reference force platform. The difference in jump height (cm) measured for the countermovement jump (CMJ: top graph), squat jump (SJ: middle graph), and drop jump (DJ: bottom graph), plotted against the average jump height (cm) for each respective jump modality. Bland-Altman (BA) plots (right graphs): the difference is defined as CoM jump height – force plate calculation. Histograms (left graphs): the number of jumps (counts) plotted against the difference in jump height. BA plots: grey solid line = line of no difference, grey dotted line = mean difference, top line = 95% confidence limits (CL), bottom line = 5% CL. The values of the mean difference, 95% CL, and 5% CL are represented to the right of the BA plot. The jumps depicted are both submaximal and maximal effort jumps, with and without arms (CMJs, and SJs), and from 20, 40, and 60 cm drop heights (DJs). Each color represents jumps performed by one participant.*

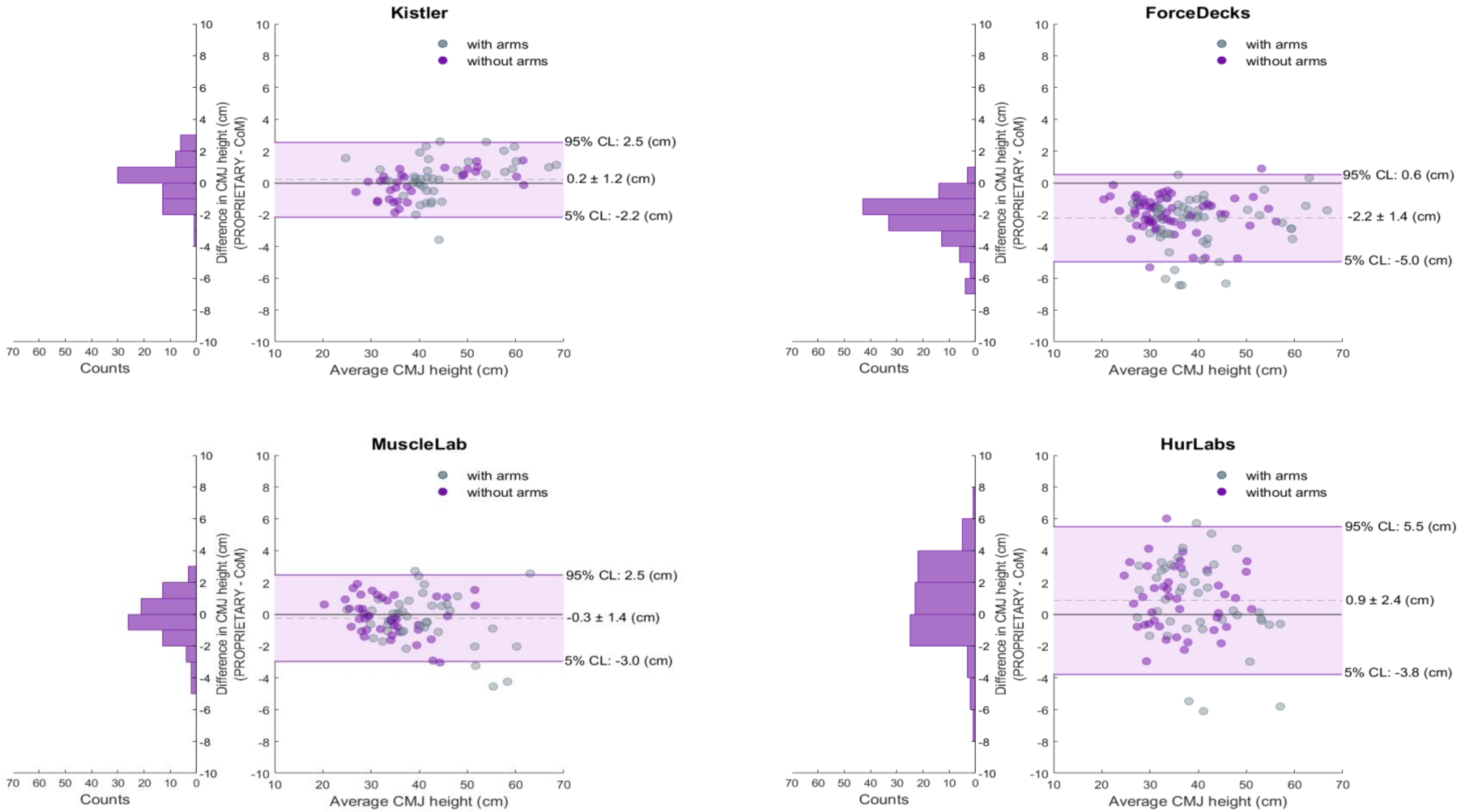

Figure 11. *The countermovement jump (CMJ). Comparison between the center of mass (CoM) analysis and proprietary software calculations from each of the included portable force platform systems. The difference in CMJ height (cm) is plotted against the average CMJ height (cm). Bland-Altman (BA) plots (right graphs): the difference is defined as proprietary software calculation – CoM calculation. Histograms (left graphs): the number of CMJs (counts) plotted against the difference in CMJ height. BA plots: grey solid line = line of no difference, grey dotted line = mean difference, top line = 95% confidence limits (CL), bottom line = 5% CL. The values of the mean difference, 95% CL, and 5% CL are represented to the right of the BA plot. Grey dots: jumps performed with arm swing. Purple dots: jumps performed with arms on the hips. The jumps depicted are both submaximal and maximal CMJs.*

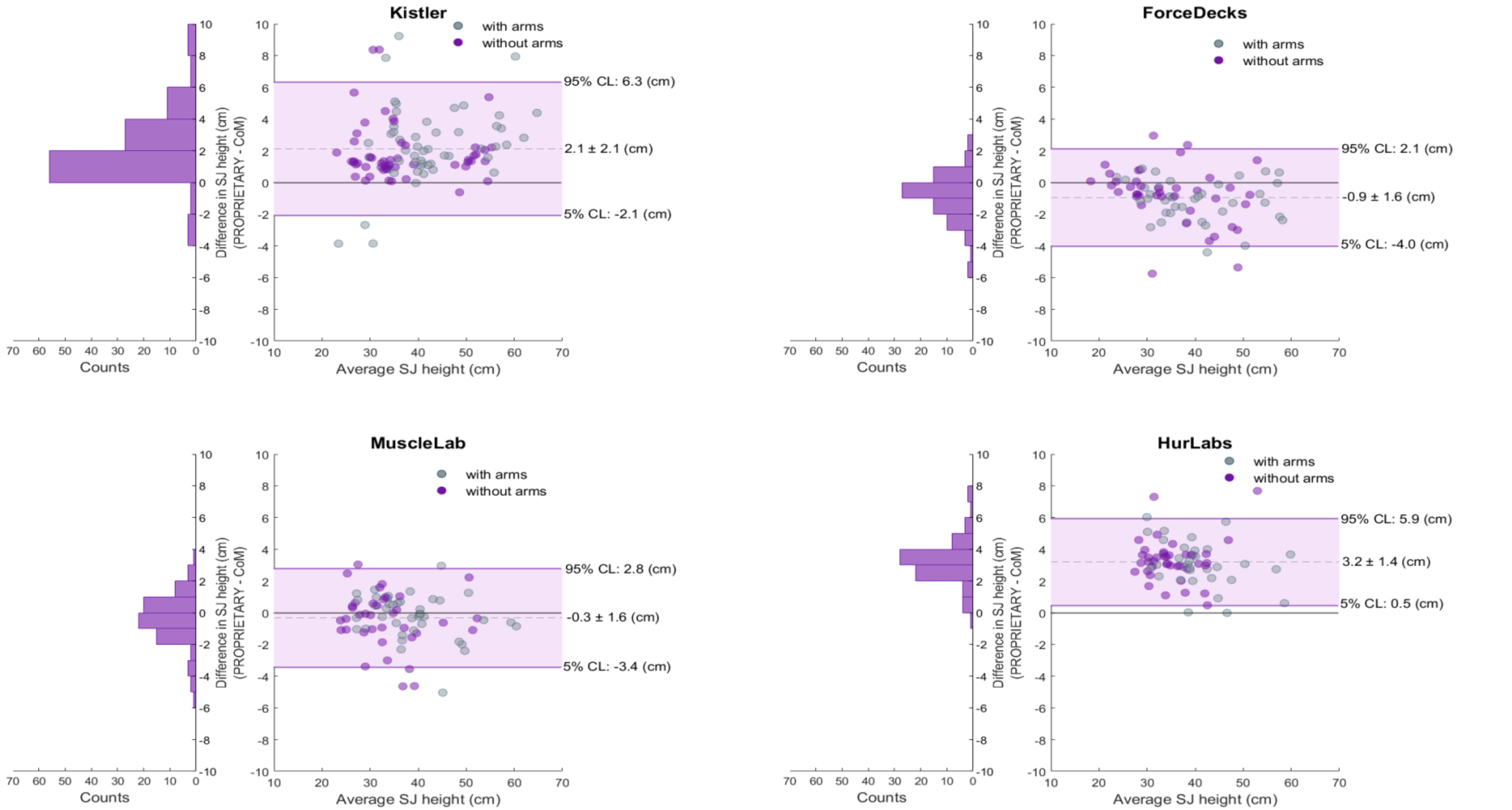

Figure 12. *The squat jump (SJ). Comparison between the center of mass (CoM) analysis and proprietary software calculations from each of the included portable force platform systems. The difference in SJ height (cm) is plotted against the average SJ height (cm). Bland-Altman (BA) plots (right graphs): the difference is defined as proprietary software calculation – CoM calculation. Histograms (left graphs): the number of SJs (counts) plotted against the difference in SJ height. BA plots: grey solid line = line of no difference, grey dotted line = mean difference, top line = 95% confidence limits (CL), bottom line = 5% CL. The values of the mean difference, 95% CL, and 5% CL are represented to the right of the BA plot. Grey dots: jumps performed with arm swing. Purple dots: jumps performed with arms on the hips. The jumps depicted are both submaximal and maximal SJs.*

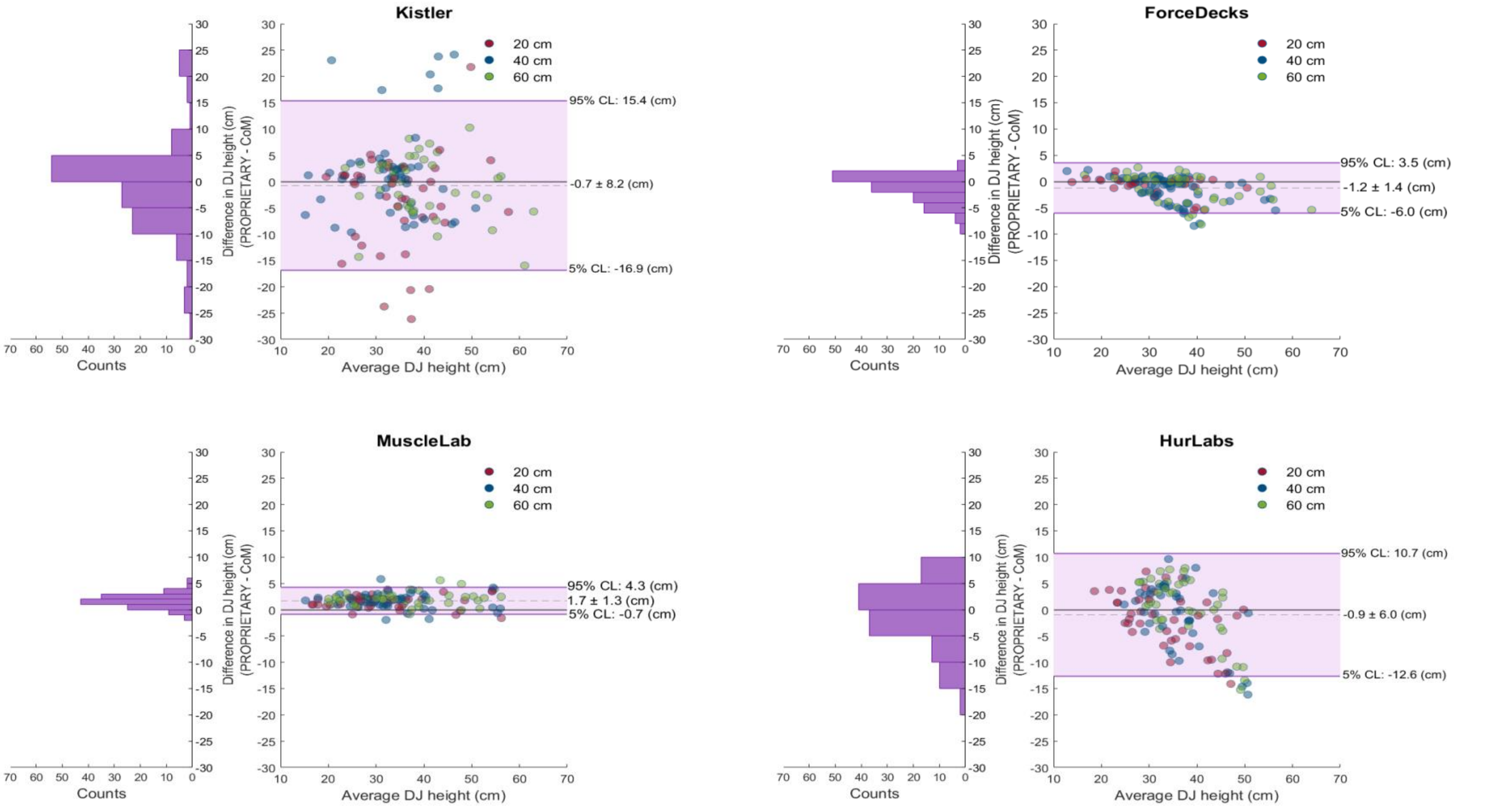

__Figure 13.__ The drop jump (DJ). Comparison between the center of mass (CoM) analysis and proprietary software calculations from each of the included portable force platform systems. The difference in DJ height (cm) is plotted against the average DJ height (cm). Bland-Altman (BA) plots (right graphs): the difference is defined as proprietary software calculation – CoM calculation. Histograms (left graphs): the number of DJs (counts) plotted against the difference in DJ height. BA plots: grey solid line = line of no difference, grey dotted line = mean difference, top line = 95% confidence limits (CL), bottom line = 5% CL. The values of the mean difference, 95% CL, and 5% CL are represented to the right of the BA plot. Red dots: jumps performed from a 20 cm box height. Blue dots: jumps performed from a 40 cm box height. Green dots: jumps performed from a 60 cm box height. The jumps depicted are both submaximal and maximal DJs.

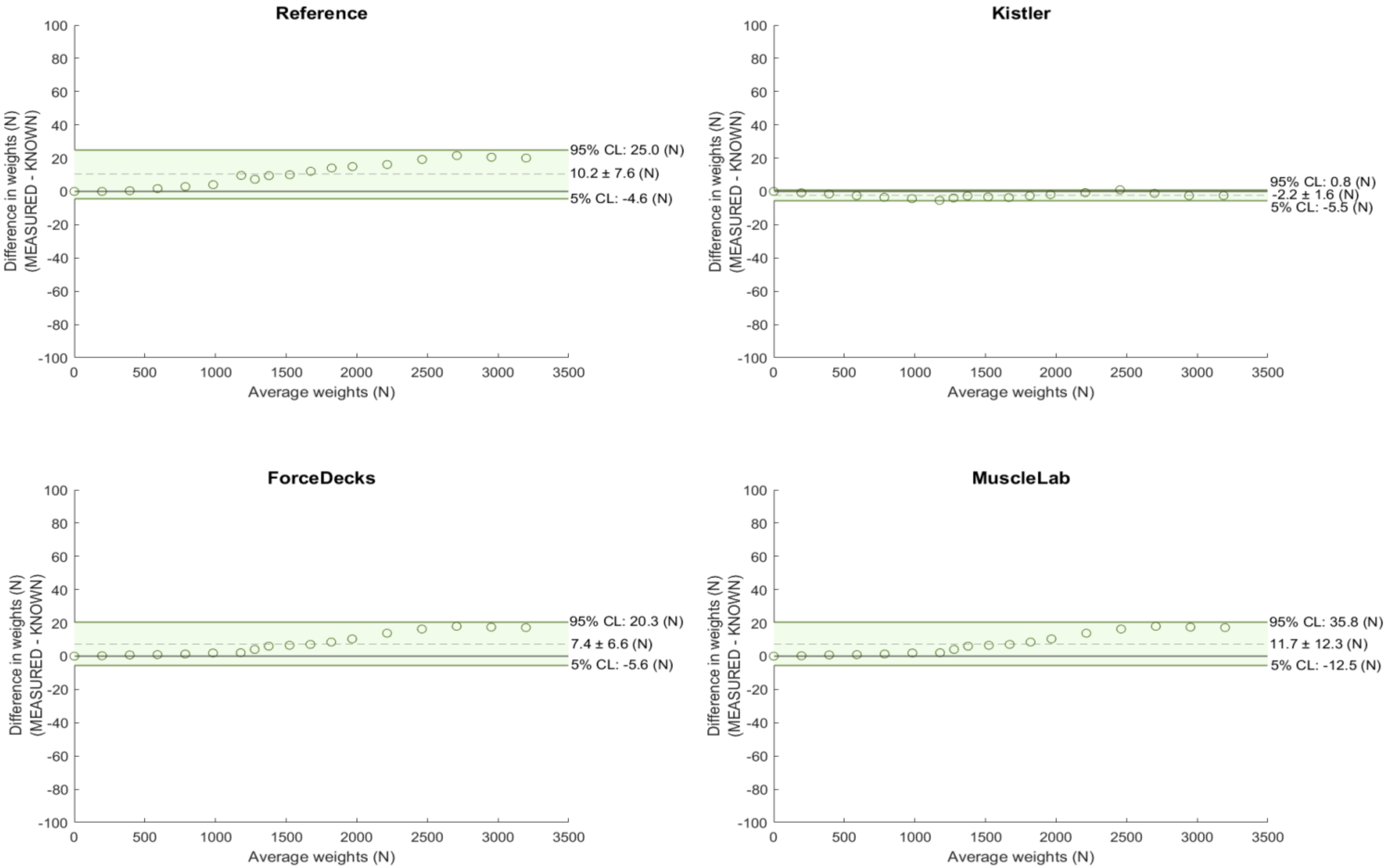

Figure 14. *Difference between the measured weights and the known weights (N) during loading conditions for each of the included force platform systems (except for HurLabs), plotted against the average weights (N), as Bland-Altman (BA) plots. Grey solid line = line of no difference, grey dotted line = mean difference, top line = 95% confidence limits (CL), bottom line = 5% CL. The values of the mean difference, 95% CL, and 5% CL are represented to the right of the BA plot.*

Table 6. *Differences between measured and known weights for the loading, unloading, and load versus unload conditions, the range of differences, and the load at the maximum and minimum difference, for the included force platform systems.*

Condition	Force plates	Mean ± SD (N)	Range (max – min)	Loads at max diff (kg)	Loads at min diff (kg)
Loading	*Reference*	8.9 ± 7.3	20.6–0.0	275	0
	Kistler	–2.4 ± 1.6	5.4–0.0	120	0
	ForceDecks 1	7.4 ± 6.6	18.0–0.0	275	0
	ForceDecks 2	7.3 ± 6.8	18.1–0.0	275	0
	MuscleLab	11.7 ± 12.3	35.1–0.0	325	0
Unloading	*Reference*	9.9 ± 6.9	20.9–0.9	275	0
	Kistler	–2.6 ± 1.7	5.5–0.2	120	0
	ForceDecks 1	7.4 ± 6.6	17.9–0.0	275	0
	ForceDecks 2	7.4 ± 6.8	18.2–0.0	275	20
	MuscleLab	14.1 ± 11.7	35.0–1.2	325	0
Load vs. unload	*Reference*	0.4 ± 0.4	1.1–0.0	20	225
	Kistler	–0.1 ± 0.2	0.4–0.1	130	325
	ForceDecks 1	0.0 ± 0.1	0.1–0.0	200	325
	ForceDecks 2	0.1 ± 0.2	0.4–0.0	0	60
	MuscleLab	2.4 ± 1.0	3.6–0.1	120	325

Abbreviations: SD, standard deviation; max, maximum difference; min, minimum difference; diff, difference; N, newtons; kg, kilograms; vs., versus. ForceDecks 1 and ForceDecks 2 represent each of the dual force platforms.

Discussion

The aim of this study was to compare jump heights from four different force platform systems against a reference force platform system and to determine if differences between the systems were mainly attributed to differences in data processing ("software") or the force recording *per se* ("hardware"). The main findings were that all portable force platform systems differed significantly from each other, supporting our initial hypothesis. Based on our results, these differences were attributed to both the hardware and software, but in agreement with our second hypothesis, the data processing method ("software") was clearly most important.

This is the first study to examine the agreement in jump heights measured by several commercially available force platform systems, testing both the hardware and software components, including several jump modalities (CMJs, SJs, and DJs) over a large range of jump heights (~ 10 to 70 cm). Previous studies investigating the accuracy of portable force platforms have not reported jump height, have investigated the agreement between only a single force platform system against a reference system, have not examined the accuracy of the software calculations, and included few jumps from one jump modality (either the CMJ or DJ) over a moderate range of jump heights (Walsh et al., 2006; Buckthorpe et al., 2012; Silveira et al., 2017; Lake et al., 2018; Raymond et al., 2018).

4.1 Hardware Analysis

All portable force platform systems differed to some extent from the reference in-ground force platform, even when identical calculation procedures were applied (Table 4). These results imply that there were slight differences in the GRF-time curves measured by different force platform systems, which rendered them to respond to a given calculation differently.

The Kistler force platform was the only force platform that systematically overestimated jump height compared with the reference force platform for all jump modalities (Figures 4, 5, and 6). Indeed, the Kistler force platform was significantly different from all other included force platforms (Table 5). These findings were not as expected as the Kistler force platform is the most commonly used, expensive (high-end) portable force plate system.

We suspected to find a reason for these systematic differences and started exploring this by simply comparing the GRF-time curves measured by the Kistler force platform and the reference force platform against each other. The GRF-time curves were different, and it seemed as if the Kistler system applied the incorrect sampling frequency, where the sampling frequency was declared to be 1000 Hz.

Every force platform system uses quartz crystals as the oscillator to measure time. These clock crystals are driven by a voltage change which renders them to vibrate at their resonance frequency, which is by consensus tuned to 32786 Hz. Sampling at 1000 Hz is simply not possible with a clock frequency of 32786 Hz, as it would require one sample every 32.786 clock ticks (rather than every 32 or 33 clock ticks). Force platform systems account for this, which seemed to be the step missing in the Kistler system. Through experimentation, it became evident that the sampling frequency of the Kistler force platform was not 1000 Hz, but rather 1024 Hz (Figure 15). In this example we compared the force signal from the Kistler force platform to the reference force data, setting the sampling frequency at 1000 Hz (which is the frequency declared in the raw data files), 1024 Hz (expecting the data to be sampled every 32 clock ticks), and 992.9697 Hz (expecting the data to be sampled every 33 clock ticks). By changing the sampling frequency of the Kistler force platform from 1000 Hz to its actual sampling frequency of 1024 Hz, the on average 3.7% overestimation in jump heights observed in the Kistler system for all jump modalities (Table 4) changes to an underestimation of on average 1% for all jump modalities—making the Kistler force platform equally, or in fact slightly superiorly, accurate to the other portable force platform systems included in this study.

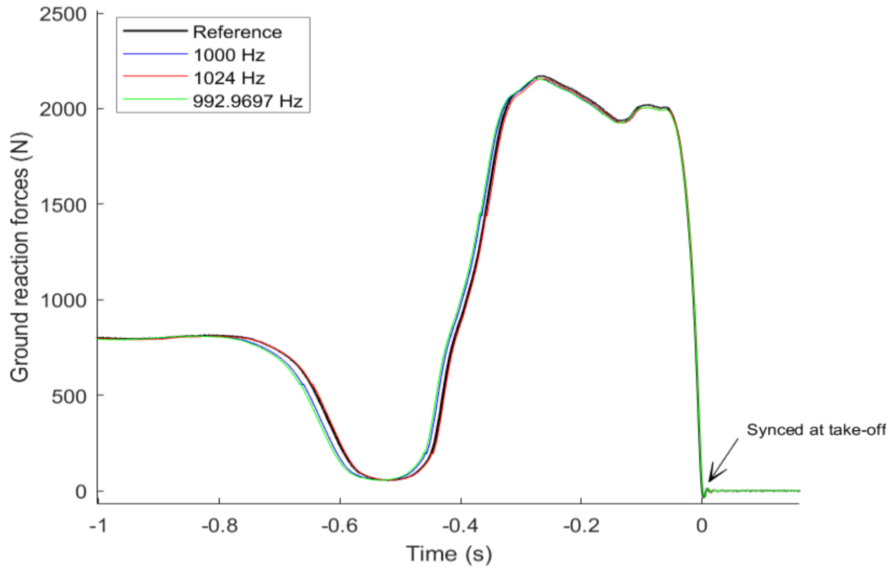

Figure 15. *Example of the ground reaction forces (N) over time (s) in a countermovement jump measured by the Kistler force platform at various sampling frequencies (blue, red, and green color), and the reference force platform (black). The reference force platform sampled at 2000 Hz.*

After correcting for the sampling frequency, the findings in jump height calculation accuracy of the Kistler force plate seems to be consistent with the high accuracy in the static tests (Table 6 and Figure 14).

Superior accuracy in static testing is, however, not necessarily of importance for dynamic measures such as jumping. Especially for CMJs and SJs, where forward integration procedures were applied, the average peak force prior to take-off reached ~ 1733 N, indicating how deviations in force measures above this value (as present in the strain gauge force platforms) would not affect jump height. However, peak forces at landing were on average ~ 3800 N, reaching > 10 000 N in certain instances, indicating how the results from the static testing could affect the DJ height calculations (as we applied a backward integration procedure over the landing phase). On that note, the strain gauge force platforms showed tendencies of slightly overestimating the measured force at force values greater than ~ 1000 N. Indeed, compared to the Kistler force platform, our reference strain gauge force platform overestimated the maximum measured peak forces at landing by on average 840 N. If viewed in isolation, this would imply underestimated DJ heights measured by the Kistler system, which was not the case (Figure 6).

If Kistler was superiorly accurate compared with any of the included strain gauge force platforms for DJ assessments, it should be mirrored in the CoM analysis (if we assume the

CoM model measures the “correct” jump height). However, as the Kistler system on average overestimated DJ heights and the CoM model underestimated DJ heights, compared with the reference system, our data does not support these assumptions. Hence, accuracy in static testing does not necessarily translate into superior accuracy for dynamic measures such as jumping.

The reason why the correct sampling frequency of the Kistler system was not accounted for in our initial analysis, was simply because we intended to use the force platform systems as they are reported to be used by researchers and practitioners. The Kistler system states that the sampling frequency is, in this case, 1000 Hz, and studies using the Kistler force platform have reported the sampling frequency to be 1000 Hz (similar reports have been seen for sampling frequencies of 500 and 2000 Hz) (Bobbert & Schamhardt, 1990; Kibele, 1998; Baca, 1999; Vanrenterghem et al., 2004; Psycharakis & Miller, 2006; Barr & Nolte, 2011; Meylan et al., 2011; Coh & Mackala, 2013; Owen et al., 2014; Judge & Burke, 2015; Silveira et al., 2017; Barker et al., 2018; Harrison et al., 2019; Wank & Coenning, 2019; Harry et al., 2020; Lake et al., 2020; Philpott et al., 2020; Sahrom et al., 2020; Kennedy & Drake, 2021; McMahon et al., 2022; Wade et al., 2022; Williams et al., 2022). The fact that the Kistler corporation states that their force platforms sample at e.g., 500, 1000, or 2000 Hz should be corrected. These considerations are of concern if extracting the raw data and applying your own algorithm to it—which is a popular practice applied by most researchers (Wank & Coenning, 2019; Harry et al., 2020; Lake et al., 2020; Philpott et al., 2020; Sahrom et al., 2020; Kennedy & Drake, 2021; McMahon et al., 2022; Wade et al., 2022).

The MuscleLab system showed on average the best agreement over all with the reference force platform when measuring CMJ and SJ heights, although displaying the largest TEEs% compared with the other force platform systems, for all jump modalities (Table 4). The greater TEEs% observed for all jump modalities in the MuscleLab system mirrors the large spread in the data, seen in Figures 4, 5, and 6. In fact, differences in jump height of up to ~ 7 cm were present when jump height was calculated through the same algorithm. As with the Kistler force platform, the MuscleLab force platform was significantly different from the other included force platforms (Table 5).

The clearest difference between the MuscleLab system and the reference force platform, or any of the other included force platforms, is its lower sampling frequency. The MuscleLab system sampled at 200 Hz, which is in comparison to the 2000 Hz sampling frequency of the reference platform, and ≥ 1000 Hz sampling frequencies for the other included force platform systems. A lower sampling frequency affects the point of take-off (Street et al., 2001), which is relevant for CMJs and SJs when using the velocity at take-off to estimate jump height, as was done in this study. More specifically, it has been stated that when sampling at frequencies < 1000 Hz, the point of take-off has, most likely, been selected late (Street et al., 2001). The point of take-off measured by the MuscleLab system was in fact selected late, which was indicated by a force of –11 ± 15 N at take-off for both the CMJs and SJs, in comparison to the superiorly robust force at take-off for these jump modalities obtained by the reference force platform (6 ± 3 N). A late selection of take-off results in an increased negative impulse, and as such underestimated jump height (Street et al., 2001; Pérez-Castilla et al., 2021). However, there was no clear pattern showing underestimated CMJ heights when measured by the MuscleLab system compared with the reference force platform (MuscleLab overestimated CMJ heights by 0.1%). For the SJs, the MuscleLab system underestimated jump heights by 1.0%, which was lower than the underestimations observed for ForceDecks (1.7%) and HurLabs (1.5%) in the same jump modality, where sampling frequencies were ≥ 1000 Hz. These results highlight how even though the lower sampling frequency of the MuscleLab system resulted in a late selection of take-off, choosing a correct point of take-off is not the only potential source of error when analyzing jump height using a force platform.

Peak forces could be attenuated at low sampling frequencies, as certain data points are skipped (Hori et al., 2009; McMaster et al., 2014). Attenuated peak forces would result in underestimated jump heights. Peak forces prior to take-off measured by the MuscleLab system (200 Hz) were almost identical to those measured by the reference force platform (2000 Hz), measuring in fact slightly higher peak forces for both the CMJs (MuscleLab: 1744 ± 280 N, reference: 1724 ± 272 N) and the SJs (MuscleLab: 1775 ± 295, reference: 1755 ± 288 N). Thus, the low sampling frequency did not impact peak force prior to take-off measured by the MuscleLab system.

The slightly overestimated peak forces might be explained by the MuscleLab system overestimating force by on average 2.2% for CMJs, and 0.5% for SJs. Even though these are arguably small overestimations they might have contributed to the less obvious underestimation which could be attributed to the late selection of take-off. However, body weight was also overestimated by on average 0.9% for the CMJs and 1.1% for the SJs. Overestimated body weight should result in lower jump heights. Since body weight was overestimated to a slightly greater extent in the SJs, and force was in general slightly less overestimated, compared with the CMJs, this could explain why there were clearer tendencies for SJ heights to be underestimated compared with CMJ heights (Figures 4 and 5). However, the specific influence these differences have on CMJ and SJ heights needs to be examined in a future study.

For DJs, the low sampling frequency clearly contributed to the average overestimated DJ heights of 2.3% measured by the MuscleLab system (Figure 6). In fact, body weight was overestimated by 1.1%, and peak force at landing was underestimated by 3.4% in the MuscleLab system compared with the reference force platform, indicating underestimated jump heights. The average overestimated DJ heights observed in the MuscleLab system was explained by a late selection of landing. The late selection of landing was indicated by forces of 120 ± 130 N at the defined landing threshold, which is in comparison to forces of 20 ± 11 N at landing measured by the reference force platform. The late selection of landing was due to the low sampling frequency, which becomes evident in Figure 16. In Figure 16, it is clear how landing was selected late, as there were simply no data points to choose from during such rapid changes in force, when sampling with frequencies of 200 Hz. Obviously, these considerations need to be addressed alongside our set landing definition, where we choose the first data point after a threshold of 10 N, which many studies report using (Pérez-Castilla & García-Ramos, 2018; Peng et al., 2019; Chiu & Dæhlin, 2020; Montalvo et al., 2021).

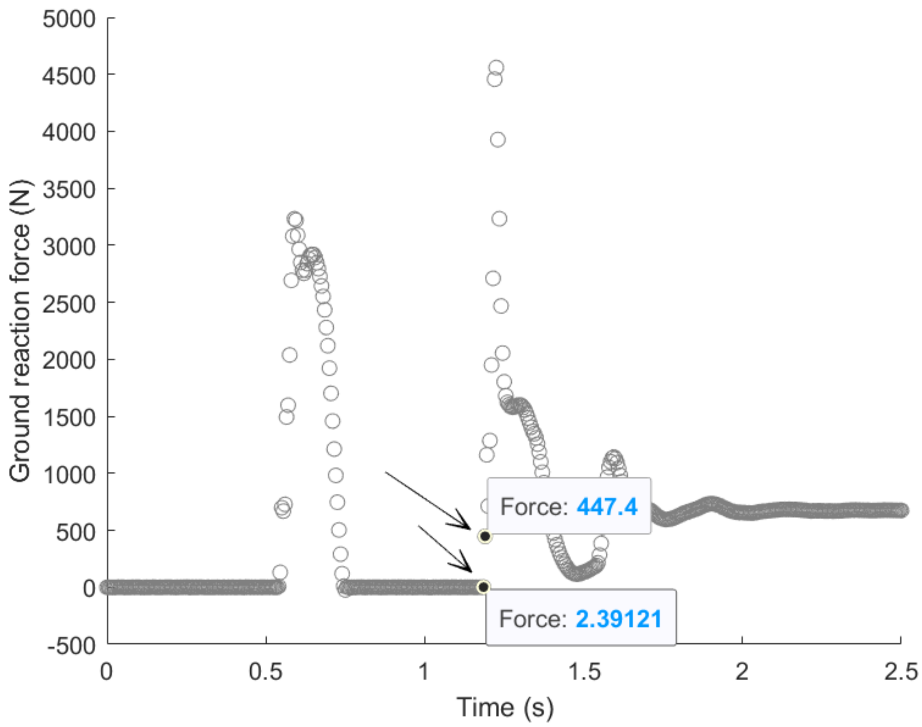

Figure 16. *Example of the ground reaction forces (N), sample-by-sample, over time (s) from a drop jump measured by the MuscleLab force platform, sampling at 200 Hz. The arrows depict the two force values closest to the point of landing.*

Our findings highlight how the conventional methods of selecting take-off and landing are not suited for force platforms sampling at 200 Hz, particularly not if backward integration over the landing phase is used to calculate jump height. However, our observations do not indicate that force platforms sampling at 200 Hz are useless for jump height measures, they simply indicate that we need to define take-off/landing differently than for force platforms sampling with higher frequencies. A solution would be to e.g., interpolate the data points so that one could define an imaginary point at e.g., 10 N prior to take-off/after landing, or oversample the data. In view of the number of force platforms sampling at low sampling frequencies, future studies are encouraged to investigate a robust definition of take-off and landing for force platforms sampling at 200 Hz.

The larger spread in jump heights observed for the MuscleLab system, compared with the other force platform systems, for all jump modalities (Figures 4, 5, and 6), should not be neglected and could mirror a myriad of different factors. One obvious assumption would be variability in the measured body weight. The variation in body weight was on average 3.1% larger in the MuscleLab system, for all jump modalities, as compared with the reference force platform. Previous studies have reported how small errors in body weight could cause large errors in jump height, due to errors accumulating during integration procedures (Kibele, 1998; Street et al., 2001; Vanrenterghem et al., 2001). Indeed, in the study by Street et al. (2001) an error of only 0.13% in body weight caused 26 times larger errors in CMJ heights. Similar findings were observed in a simulation study conducted by Vanrenterghem et al. (2001) where a within-trial variability of 1.7% in body weight caused an error of 4.5 cm in CMJ heights. In fact, Street et al. (2001) experimented by increasing body weight by 0.25% in all the participants, which caused a 6.5% underestimation in jump height. Considering these findings, it is likely that the variability in measured body weight caused the large spread in jump heights as observed for the MuscleLab system.

Another possible explanation for the large spread in jump heights in the MuscleLab system could be the noise associated with the portable force platform. For example, the fact that the MuscleLab force platform was not anchored to the ground could yield greater noise in the force signal at e.g., the point of take-off. In fact, the variability in force at take-off measured by the MuscleLab system was five times that of the in-ground reference force platform for the CMJs and SJs (15 N vs. 3 N). However, none of the included portable force platforms were anchored to the ground, and much smaller TEEs% were present (Table 4), where the variations in force at take-off were well within 6 N for all force platform systems. Thus, it is possible that the large variability in force at the point of take-off, measured by the MuscleLab system, was due to its low sampling frequency.

The reason why the MuscleLab system agreed best with our reference system on average, was simply because the errors in the MuscleLab system affected jump height in opposite directions. As the errors apparently cancelled each other out, the average differences were negligible. For example, for CMJs the average difference in jump height between the MuscleLab system and reference system was 0.0 cm, although the variation was 1.8 cm. Indeed, the CMJs measured by the MuscleLab system showed the largest TEEs% of all jump modalities and force platform systems, reaching 5%. It is especially likely that the random discrepancies observed in the MuscleLab system were influenced by the low sampling frequency and the large variability in measured body weight.

The ForceDecks and HurLabs force platform systems showed equally small percentage mean differences from the reference force platform, underestimating jump height by on average 1.4% (ForceDecks) or 1.8% (HurLabs). Moreover, these force platform systems showed the lowest TEEs% of 1.6% on average for all jump modalities (Table 4). Indeed, for CMJ and SJ height measures, ForceDecks and HurLabs did not differ from each other although both systems differed significantly from the Kistler and MuscleLab systems (Table 5).

The slight systematic underestimation observed for all jump modalities in these force platform systems could mirror an overestimation in measured body weight. ForceDecks on average overestimated body weight by 1.3% for all jump modalities, and HurLabs by 1.2%, when compared with body weight measured by the reference force platform. However, as with the MuscleLab system, ForceDecks and HurLabs overestimated the force produced prior to take-off/after landing by on average 1.2% (ForceDecks) and 1.8% (HurLabs), which should offset a negative effect of slightly increased body weight for jump height measures. Whether overestimated body weight had a greater influence on jump height than overestimated force production, remains to be investigated.

In the case of the ForceDecks system, the slight underestimations in jump heights could also mirror take-off selected slightly later than by our reference force platform for CMJs and SJs (ForceDecks: 4 ± 3 N, reference: 7 ± 3 N). Hence, the overestimated body weight and later selection of take-off most likely contributed in conjunction to the slightly underestimated tendencies in jump heights measured by the ForceDecks system. For the HurLabs system, there were no clear differences in the force at take-off for CMJs and SJs (HurLabs: 5 ± 4 N, reference: 6 ± 3 N), and body weight was overestimated 0.1% less than the ForceDecks system, compared with the reference system. Thus, the reason for the slight underestimation observed for these jump modalities in the HurLabs system remains unclear.

For DJs, the ForceDecks and HurLabs differed significantly from each other (Table 5), because the ForceDecks system displayed smaller discrepancies to the reference force platform, compared with the HurLabs system. In fact, it is interesting how the ForceDecks system came out the best of all included systems for DJ analysis. For the other included force platform systems, the difference from the reference system increased for the DJ analysis, in comparison with the CMJ and SJ height analyses (Table 4 and Figure 6). The reason for superior accuracy for DJ estimates in the ForceDecks system, compared with the other included force platforms, is not entirely clear.

Landing was selected late in the ForceDecks system which was indicated by forces of 35 ± 28 N at landing, which is in comparison to forces of 20 ± 9 N for the reference force platform. In addition, the ForceDecks system selected landing later than the Kistler system (25 ± 14 N) and HurLabs system (14 ± 2 N). If viewed in isolation, these results should imply overestimated DJ heights, similarly to the MuscleLab system. In fact, similar patterns were found for the ForceDecks system as those illustrated in Figure 16 for the MuscleLab system. Simply because there were not enough data points to select landing at an earlier time point with our landing definition, the force at landing reached in some instances 240 N in the ForceDecks system. In contrast, the maximum force measured at the defined landing threshold was 92 N for the Kistler system and only 20 N for the HurLabs system. One should note that the sampling frequency of the HurLabs system was 200 Hz greater than for the Kistler and ForceDecks systems. Thus, from these findings, it seems as though 1000 Hz is not sufficient to detect a proper landing threshold in certain instances, using the conventional landing definitions.

Since the ForceDecks system on average underestimated DJ heights, there must have been other factors counterbalancing the effect of a late selection of landing, resulting in better agreement with our reference system, compared to the other force platform systems.

The ForceDecks system did not over/underestimate the measured force any differently than the Kistler or HurLabs systems for DJ height analysis (ForceDecks: 1.1%, Kistler: 0.8%, HurLabs. 1.1%). Of the included force platforms peak force at landing was, however, underestimated the least in the ForceDecks system (0.3%), although differing by only 0.1% from the Kistler system. Body weight was overestimated by 1.2% in the ForceDecks system, which is in comparison to a 1.1% overestimation in the MuscleLab system, 0.6% overestimation in the Kistler system, and 1.3% overestimation in the HurLabs system. Whether the differences in body weight were sufficient to explain the differences in DJ heights, between the included force platform systems, remains unknown. From our observations, it is not clear why the ForceDecks system agreed best with our reference system.

It is important to mention how, for all force platform systems and jump modalities, most outliers were removed from the DJ data obtained by the ForceDecks system (*n* = 40 from the outlier test detecting the force data, and the criterions set in the code). The number of outliers removed for the DJ analysis was simply due to the extension frames surrounding the ForceDecks force platforms. When using extension frames, it is easy to believe that the participants have landed on the force platforms, when in fact they have slightly stepped on the foam surrounding them. If the participants have slightly landed on the extension frames, this would significantly impact the force data at landing measured by the ForceDecks force platforms, but not those of the reference system (affecting backward integration in our reference calculation). On that note, we did only include the force data which was accepted by the software, and the ForceDecks software calculations did not seem to rely on the landing data for DJ height estimates (see discussion below). One could also argue that the raw data is extracted and analyzed separately from the software calculations only in research settings, where large in-ground force platforms (as those used in this study) are available. Hence, these findings are not necessarily of any practical significance, although one should take care in relying on landing force data from portable force platforms surrounded by extension frames. From this, it is possible that data that would have contributed to the same tendencies as those observed for the other force platform systems were removed during outlier detection. The superior accuracy for DJ heights measured by the ForceDecks system could therefore simply be explained by the number of outliers removed.

The HurLabs system systematically underestimated DJ heights to the largest degree of the included force platforms but the variability (TEE%) was in line with the other force platform systems. The clearer systematic underestimation observed in the HurLabs system was probably due to the slightly greater overestimated body weight (0.2% more in the HurLabs system than the ForceDecks system). Moreover, peak force at landing was underestimated by 6% in the HurLabs system, which is a much greater underestimate than in any of the other portable force platform systems (Kistler: 0.4%, ForceDecks: 0.3%, MuscleLab: 3.4%). Thus, the force transducers of the HurLabs system might have been outside their linear range during large landing forces (> 3000 N), which could explain the superior underestimation observed in the HurLabs system when using backward integration procedures. These findings confirm some recent speculations by Wade et al. (2022), on how applying backward integration procedures is not necessarily a good option if working with certain portable force platforms. From our findings, it seems clear that one should take care in relying on backward integration procedures for certain portable force platform systems, as they might not have the capacity to tolerate high landing forces. Future studies are strongly encouraged to include portable force platform systems when investigating optimal solutions to calculate jump height from force plate recordings, as the current recommendations all stem from in-ground laboratory force platforms (Street et al. 2001; Meylan et al., 2011; Wank & Coenning, 2019; Jørgensen et al., 2021; McMahon et al., 2021; Pérez-Castilla et al., 2021; Wade et al., 2022).

In summary, the differences between the portable force platform systems and the reference system were mostly systematic, consistently increasing at higher jump heights (Figures 4, 5, and 6). The random discrepancies were small (1–2%) for all force platform systems, except for the MuscleLab system. The differences between force platform systems, showed no clear systematic pattern, as the force platform systems both over- and underestimated jump heights to various degrees, compared with the reference system. From our findings, it appears as if sampling frequency is important to consider when examining jump data obtained from different force platform systems. Nevertheless, our results indicate that the degree to which jump height was influenced by e.g., body weight variability or sampling frequencies, differed between the force platform systems included in this study.

4.2 Software Analysis

All included software calculations differed significantly from the reference calculation (Table 4), indicating how different calculation procedures impacted jump height measures, which was as expected. All included software showed large spreads in jump height differences, and as such displayed TEEs% in the range of 3% to 22%, compared with the reference calculation, which was much greater than for the Hardware analysis (1% to 5%). In contrast, the average systematic differences were not clearly greater than those of the Hardware analysis (Table 5).

Considering how both calculations were done on the same GRF-time data, there are essentially four factors that could affect any jump height differences: i) the equation used, ii) integration method, iii) body weight, and iv) integration start and stop (i.e., take-off/landing thresholds). The integration methods for the included software remain unknown for most systems and will thus not be discussed.

4.2.1 The Countermovement Jump

The Kistler and ForceDecks software slightly underestimated CMJ heights, while the MuscleLab and HurLabs software on average overestimated jump heights compared with our reference calculation (Figure 4). All jumps were calculated by using the velocity at take-off (Equation 1) so that the observed differences were not due to different equations *per se*.

The differences in CMJ heights observed by these software programs could be explained by the start of integration. Both the Kistler and ForceDecks systems defined the start of movement as an absolute value of 10 or 20 N below body weight, whereas the ForceDecks software also started integration at this point. Even though we cannot state that the Kistler software started the integration at this point, it is likely the case as this is a common procedure applied by most (Meylan et al., 2011; Pérez-Castilla et al., 2019; Donahue et al., 2021). When integration is started at such absolute values it is possible that some of the signal was lost, and more so for the ForceDecks system—which is in accordance with previous findings investigating the effect of different integration starts (Street et al., 2001; Meylan et al., 2011; Pérez-Castilla et al., 2019; Donahue et al., 2021). However, in the case of CMJs, this would result in decreased negative impulse and as such overestimated jump heights. Hence, different integration starts were not the reason for the on average underestimated CMJ heights observed in these software programs. The MuscleLab and HurLabs systems might have chosen similar integration starts, which could explain the on average overestimated CMJ heights measured by these software programs. However, as this information remains in a black box these are only speculations and should be viewed accordingly.

Another possible solution to differences in CMJ heights could be different definitions of take-off. However, the Kistler software applied a somewhat similar take-off definition to the reference calculation, using a 10 N threshold, and thus should not explain the differences in jump heights. For the ForceDecks software, the take-off threshold was 20 N, indicating how take-off might have been selected earlier than in our reference calculation. However, earlier detection of take-off should cause a decreased negative impulse, and as such overestimated jump heights. Thus, different definitions of take-off were most likely not the reason for the on average underestimated CMJ heights observed in these software programs. For the HurLabs software, a take-off threshold of 5 N was applied, indicating how take-off might have been selected later than in our reference calculation. A late selection of take-off should cause an underestimated jump height, and thus does not explain the clear overestimation in CMJ heights measured by the HurLabs software.

Differences in measured body weight could also explain the CMJ height differences shown in Figure 4. In fact, the MuscleLab software underestimated body weight by 0.9% compared with our reference calculation, which could explain the on average overestimated CMJ heights measured by the MuscleLab system. However, for the HurLabs system, which displayed the clearest overestimation in CMJ heights, body weight was minorly overestimated by 0.05% compared with our reference calculation. The ForceDecks software overestimated body weight by only 0.02%, which could perhaps explain some of the underestimations observed in the ForceDecks system. Unfortunately, the Kistler software did not include body weight as an outcome variable when exporting the software results. The reason for this is most likely the requirement of a pre-inserted body mass for each participant for the Kistler software. From this, it is possible to speculate that a pre-inserted body mass was not optimal for jump analyses and could explain the differences observed for CMJ heights (and all jump types for that matter) in the Kistler system. However, these speculations are warranted for future investigations.

The systematic over/underestimations in CMJ heights, when measured by the software, might not be of the biggest concern. What is more alarming are the random deviations with TEEs% ranging from 3% to 5%—which was larger than observed in the Hardware analysis (Table 4). The large spread in CMJ heights observed in all included software could be explained by variations in measured body weight.

To elucidate, the variability in measured body weight was 7.3% greater in the MuscleLab software compared with our reference calculation. According to the previous findings addressed above (Kibele, 1998; Street et al., 2001; Vanrenterghem et al., 2001), it is likely that the body weight variability caused the large spread in jump heights (Figure 4). However, the largest confidence interval was observed for the HurLabs system, where the jump height difference reached ~ 9 cm in certain instances. The variability in measured body weight was 0.4% smaller in the HurLabs system compared with our reference calculation. On that note, it is possible that the HurLabs calculations relied on body weight, e.g., if starting integration at a percentage of measured body weight, as has been recommended by some researchers (Meylan et al., 2011), or started integration at a defined period below body weight, similar to the ForceDecks (and likely the Kistler) system. This could, however, be the case for the MuscleLab system as well. Indeed, in a recent study by Pinto & Callaghan (2022), it was observed how small errors in body weight (0.02 ± 0.80 N, 95% confidence interval: ± 0.02 N) significantly influenced the start of movement, if defined in relation to body weight. In the study by Pinto & Callaghan (2022) these small errors in body weight resulted in a 95% confidence interval of ± 72% for the threshold of start of movement. Although Pinto & Callaghan (2022) did not report jump height results, it is possible to speculate that if integration was started at the start of movement, the variability in body weight observed in this study could affect jump height differences to a greater degree. However, these speculations should be investigated further.

For the ForceDecks software, body weight variability differed by 0.2% from our reference calculation, which could, according to previous findings addressed above (Kibele, 1998; Street et al., 2001; Vanrenterghem et al., 2001), be sufficient to cause the spread in CMJ heights observed in the ForceDecks system (95% confidence interval of ± 2.4 cm; Figure 4). It is also possible that the slight variability in body weight affected the integration start, as it was defined as the first time point in which the force values were 20 N below body weight, which would be in accordance with recent findings (Pinto & Callaghan, 2022). Thus, as discussed above, the slight variation in body weight could affect jump height to a greater degree than if only viewed in isolation. However, according to the findings of Street et al. (2001), an error of 0.2% in body weight, could cause a ~ 5% error in jump height. The error in CMJ height was only 1.3% in the ForceDecks system, indicating that other factors counterbalanced the errors associated with body weight variability. Nonetheless, of all the included software, the ForceDecks software did agree best with our reference calculation for CMJ heights. The superior agreement for the ForceDecks system could coincide with the smaller difference in body weight variability from our reference calculation, compared to the MuscleLab and HurLabs systems.

In summary, there was no systematic pattern in the differences between software calculations for CMJ heights, as jump heights were both over- and underestimated compared with our reference calculation. The random discrepancies were larger than for the Hardware analysis for all software. The reasons for the systematic under/overestimations and the random discrepancies remain unknown since they were not found to be explained by a single factor (e.g., different take-off thresholds or body weight variability), and most likely differed between the force platform systems.

4.2.2 The Squat Jump

All included software on average overestimated SJ heights compared with the reference calculation by 1.6% to 11.1%, displaying in general slightly larger/similar TEEs% than observed for the CMJs (Table 4 and Figure 5).

In the ForceDecks system, the differences in SJ heights were simply explained by different equations used to calculate jump height. Our reference calculation used the velocity at take-off while the ForceDecks software double integrated force to obtain the maximum displacement of the CoM, where the height of the CoM at take-off was then extracted from the maximum displacement. One should note that ForceDecks offers several equation options for jump height calculations, and this was the equation chosen in this study for SJ height analysis. In fact, the chosen equation from the ForceDecks software calculated jump height exactly as our calculation of the CoM model. It is interesting to see the resemblance of the overestimation in the ForceDecks software to those of the CoM model, where both calculations overestimated SJ heights by on average 0.6 cm compared with the reference calculation (Figures 5 and 11). However, when the ForceDecks calculation was compared with a sub-sample from the CoM model, the ForceDecks system underestimated SJ heights by 0.9 cm with 95% confidence intervals of ± 3.1 cm (Figure 13), indicating how the ForceDecks calculation is not necessarily superior to our reference calculation for SJ height estimates. For the other included software, SJ height was calculated using the same equation as our reference calculation (Equation 1).

For SJ analysis, researchers have stated how it is hard to achieve a steady stance in a squat position, which could affect integration start (when applying forward integration procedures) and measured body weight (if body weight is measured in the squat position) (Wank & Coenning, 2019; Lindberg et al, 2022; Wade et al., 2022). Thus, one could expect different integration starts and/or procedures to obtain body weight to explain the difference in SJ heights for the other included software. Start of integration remains unknown for most of the included software. However, if all software started integration similarly to the ForceDecks system (at e.g., 10 or 20 N) it is unlikely that integration start caused the on average overestimated SJ heights, as integration was then initiated at the ascending phase of the GRF-time curve, resulting in underestimated jump heights.

The MuscleLab system on average underestimated body weight by 0.5%, which could explain the slight overestimation in SJ heights, but is unlikely considering its random pattern. The HurLabs system overestimated SJ heights clearest with confidence limits always being positive (indicating significantly overestimated SJ heights). However, the HurLabs system overestimated body weight by on average 0.04%. Thus, it is not entirely clear that the procedures used to obtain body weight explained the overestimated SJ heights as shown in Figure 5.

Since all software showed tendencies of overestimating SJ heights, and our CoM model also slightly overestimated SJ heights, compared with the reference calculation (Figures 5 and 11), it is possible to speculate that it was in fact our reference calculation that underestimated SJ heights. However, when the proprietary software calculations were compared to the CoM model, even larger differences were observed, where the software calculations both over- and underestimated SJ heights (Figure 13). Thus, the overestimations reported by the software calculations were not mirroring the "correct" jump height.

Despite the tendencies of overestimated SJ heights, the large TEEs% should not be neglected and could be explained by the variation in measured body weight.

For the ForceDecks system, the variability in measured body weight was 0.7% greater than when measured by our reference calculation, which is in comparison to the 0.2% greater body weight variability observed for the CMJ height calculations. This could explain the spread in SJ heights measured by the ForceDecks system (Figure 5). However, the ForceDecks software measured body weight by averaging force over a 1 s period, prior to descending into a squat position (personal communication with Vald Performance). Thus, it is not entirely clear why the variability in body weight was higher in SJs versus CMJs when measured by the ForceDecks system. Additionally, even though the variability in measured body weight was 0.5% greater in the SJ calculations compared with the CMJ calculations, the confidence intervals, and TEEs% were similar between these jump modalities (Table 4, and Figures 4 and 5). Hence, for the ForceDecks system, it is not sure that greater variability in body weight explained the spread in jump heights, at least not if viewed in isolation.

One could think that since the force was double integrated by the ForceDecks software for SJ height calculations, small errors in body weight would accumulate to a larger degree and cause greater differences in jump height. In fact, in the study by Pinto & Callaghan (2022), it was recommended to average body weight over a 2 s period if double integrating the force signal, as a 0.08% difference in body weight (reported from a 1 s averaging period) caused an 8.7% difference in take-off displacement, due to errors accumulating during integration. However, since the TEEs% were similar for the CMJ and SJ calculations, it is not clear that body weight variability affected the double integration of the force signal—although, it is possible that the TEEs%, though of similar magnitudes, were affected by different factors for the CMJ and SJ calculations.

For the MuscleLab system, the variation in measured body weight was 6.6% greater than when measured by our reference calculation, which is in comparison to the 7.3% greater body weight variability observed for CMJs. Indeed, the confidence intervals and TEEs% were similar in the SJ and CMJ analyses. Thus, for the MuscleLab system, it does not seem that body weight was inferiorly measured in the SJ versus the CMJ.

For the HurLabs system, the variability in measured body weight was 1.1% greater than measured by our reference calculation, which is in comparison to the 0.4% lower body weight variability observed for CMJ calculations. However, the confidence intervals and TEEs% were similar in the SJ compared with the CMJ analysis (Table 4, and Figures 4 and 5). On the contrary, SJ showed greater systematic tendencies (always overestimating jump height), compared with CMJ analysis. Thus, it is not clear that the random deviations in jump heights were explained by the larger variability in measured body weight by the HurLabs system.

In summary, from our results, it seems as though an overestimated SJ height should be expected if relying on software calculations. The reason for these overestimations most likely differed between the force platform systems. The random deviations (TEE%) were on average slightly larger/similar for SJ heights compared with CMJ height calculations for all force platform systems, for reasons that are not clear through our analyses.

4.2.3 The Drop Jump

All included software underestimated DJ heights to various degrees, except for the MuscleLab software which displayed the strongest agreement with the reference calculation (Table 4 and Figure 6). The differences between software calculations were simply due to different methods used to calculate DJ height. There are essentially three options to calculate DJ heights: i) the flight-time method, ii) estimating touchdown velocity based on the drop height, and iii) applying backward integration procedures.

Our reference calculation applied a backward integration procedure to calculate DJ heights which has been recommended by some researchers (Wank & Coenning, 2019; Wade et al., 2022). It is noteworthy how the MuscleLab system agreed best with the reference calculation for DJ analysis (Figure 6), which makes it clear that the MuscleLab software also calculated DJ heights using backward integration (personal communication with MuscleLab). Moreover, it was obvious that the MuscleLab system relied on the landing data as the DJs were not approved by the software unless the participants landed on the force platform and came to a still position within 1 s. Indeed, body weight measured by the MuscleLab software, and our reference calculation were identical. On that note, even though the average difference only reached 0.2 cm, the 95% confidence interval was ± 2.4 cm, which is interesting considering that the same GRF-time data was calculated with the same method (backward integration). These results highlight how even when applying identical methods/equations, differences in data processing steps, e.g., start of integration, take-off/landing thresholds, will impact jump height measures. However, in the Hardware analysis, the exact same calculation procedures were applied, and the differences were much larger than for the Software analysis (Figure 6). For sure, there are myriads of factors affecting jump height outcomes when measured by the force platform.

The largest random deviations in DJ height estimates were observed in the Kistler and HurLabs systems, where both software estimated the touchdown velocity based on drop height. Drop height can be estimated by simply setting the box height as the drop height and from there using the box height to estimate touchdown velocity, through the principle of energy conservation. In fact, both the Kistler and HurLabs software relied on an inserted box height for drop height estimates. One should note the larger differences in DJ heights in these software programs compared with the ForceDecks and MuscleLab calculations, with TEEs% of 16% for the HurLabs system, and 22% for the Kistler system (Table 4).

Indeed, estimating drop height based on box height has been advised against for decades, due to inaccurate velocity estimates (Bobbert et al., 1986; Baca, 1999; Kibele, 1999; Wank & Coenning, 2019; McMahon et al., 2021).

The lack of accuracy in estimated touchdown velocity when box height is inserted is simply because participants tend to elevate their CoM when dropping from low box heights (20 cm), while lowering the CoM when dropping from higher box heights (40–60 cm)—which in turn would lead to the box height under- (at low box heights) or overestimating (at higher box heights) actual drop height (Bobbert et al., 1986; Kibele, 1999). However, studies have also reported how the box height overestimates drop height at low box heights (20 cm) by up to 5.13 cm (Geraldo et al., 2019). Nonetheless, to the best of our knowledge, all studies that have investigated this phenomenon have reported how actual drop height differs from box height by on average 0.71–12.5 cm, where the absolute difference escalates with increases in drop heights (Bobbert et al., 1986; Kibele, 1999; Costley et al., 2018; Geraldo et al., 2019; McMahon et al., 2021). Interestingly though, from our findings, it seems to be no clear pattern showing that differences in DJ heights change with increases in drop heights (Figure 6). We do, however, need to consider how the large TEEs% could be affected by variations in actual drop heights, which were not accounted for when drop height was estimated from box height.

The most obvious systematic difference was observed in the ForceDecks system where the underestimation clearly increased with increased jump heights (Figure 6). The ForceDecks system calculated DJ heights based on the flight-time method, assuming that the participants were in the same position during take-off and landing (personal communication with Vald Performance). It makes sense that ForceDecks would choose such an approach as it does not require landing data, and the DJ height calculations from the ForceDecks system were not affected by the participants slightly landing on the extension frames. In fact, Baca (1999) recommended the flight-time method over using the box height to estimate drop height, for DJ height analysis, although the flight-time method is not without limitations.

The flight-time method is usually reported to overestimate jump heights, compared with using the velocity at take-off, by 0.6 to 4.1 cm (Kibele, 1998; Baca, 1999; Aragón-Vargas, 2000; Moir, 2008; Wank & Coenning, 2019; Chiu & Dæhlin, 2020; Wade et al., 2020;

Lindberg et al., 2021). The observed overestimation when jump height is calculated through the flight-time method is simply due to participants slightly bending their legs whilst in the air, which artificially increases flight-time, and as such jump height (Kibele, 1998; Baca, 1999; Moir, 2008; Wade et al., 2022). Interestingly though, our findings did not confirm this theory. On that note, the CoM model also underestimated DJ height compared with our reference calculation, indicating how it could be the reference calculation overestimating DJ heights. However, similar systematic underestimations were observed when the ForceDecks calculation was compared with the CoM model (Figure 13), indicating how their calculation might not be the best option for DJ height calculations at high jump heights.

In summary, the different software applied different procedures to calculate DJ heights. The superiorly systematic differences were found in the software that did not use box height to estimate drop height. For the latter method, large random discrepancies were observed (TEEs% of 16% and 22%). Thus, from our results, and from previous findings, it is evident that one should not use the box height as an estimate of drop height for DJ analysis. We encourage all commercially available software to stop estimating drop height based on the box height for DJ height estimates, and rather employ methods resembling the MuscleLab and ForceDecks systems.

4.3 CoM Analysis

Jump height measured from 3D motion capture as the vertical displacement of the CoM was included as an alternative reference, well aware that this method is not without errors. The CoM model used in this study overestimated CMJ heights by on average 0.9 cm, SJ heights by on average 0.6 cm, and underestimated DJ heights by on average 0.6 cm (Figure 10). Alternatively, the reference calculation under/overestimated jump heights by these factors. Importantly, the model used in this study stems from the Visual 3D software, which uses cadaver-derived values provided by Dempster (1955) as an input to estimate the segment mass and segment center of mass. Kibele (1998) used the Dempster method for CMJ height calculations and reported overestimations of up to 2 cm for CMJ heights, which is in accordance with our findings. The lower overestimation observed in this study compared with those provided by Kibele (1998) could mirror the lower sample size in the study by Kibele (1998) ($n = 4$ vs. $n = 14$), where each participant performed only one jump in the study by Kibele (1998), as opposed to > 400 included jumps in this study. In the study by Wade et al. (2022), the CoM used for jump height measures was also obtained from the Visual 3D software, and a similar set-up to the one used in this study was applied, examining 22 participants performing > 200 maximal and submaximal CMJs. In the study by Wade et al. (2022), the kinematic model resulted in an overestimation by on average 0.4 cm, which is slightly lower than those observed for CMJs in this study, though with a larger variation than observed in our study. Thus, our findings are in somewhat agreement with previous findings on CMJ heights.

As discussed by Kibele (1998), it is possible that the CoM model overestimated CMJ and SJ heights as the body might not have been fully extended at take-off. From this, it is possible that the CoM at landing was slightly higher than when the feet are on the ground, which could explain the on average underestimated DJ heights, although this should be investigated. Moreover, as the Dempster method assumes the body to be rigid, the countermovement amplitude (in CMJs) was reported by Kibele (1998) to be lower in the Dempster model than those of the force plate data, simply because the trunk tends to bend slightly during countermovement. Moreover, although not examined for jumping, it has been stated the Dempster model is not suited for CoM computations in young individuals, both males and females, like those included in this study (Virmavirta & Isolehto, 2014). Indeed, it is not sure that the Dempster model is suited for whole-body CoM computations, and from there jump height calculations, at all.

Even though the CoM analysis did prove useful in this study, we do not feel confident to conclude our CoM model was superior to our reference calculation from force platforms for jump height estimates.

Practical Applications

The purpose of this study was to inform researchers and practitioners about the expected differences in jump height when measured by different force platform systems. We did not intend to propose which force platform system that is best suited for jump assessments. In fact, regardless of the force platform used, our results indicate that all force platform systems have limitations, and it is important that users are aware of these.

Our results highlight how even when applying identical jump protocols and calculation procedures, there were differences in jump height measured by different force platform systems. Thus, different force platform systems should be used interchangeably with caution, even when applying the same algorithm. In general, one could expect differences of up to ~ 2 cm when using different force platforms, which is arguably small but large enough in many instances. Especially when testing elite and high-performing athletes, differences in jump heights have been reported to be ~ 0.4 cm for SJs and CMJs over a period of 2 to 6 months (Lindberg et al., 2022). In this case, the jump height differences between force platform systems observed in this study would be unacceptable if athletes were to be tested at different force platform systems. Thus, even greater care must be taken when testing high-performing athletes, especially as the differences were inflated at higher jump heights (> 40 cm).

A practical example of how the included software can be used interchangeably is given in Table 7. Table 7 outlines the expected differences between software on average for all jump modalities included in this study.

Table 7. *Differences in jump heights between the proprietary software calculations for all jump modalities.*

Software	*ForceDecks (cm)*	*MuscleLab (cm)*	*HurLabs (cm)*
Kistler (cm)	0.6 ± 1.9	1.9 ± 2.0	2.8 ± 2.3
ForceDecks (cm)		1.2 ± 1.2	2.4 ± 1.7
MuscleLab (cm)			2.4 ± 1.7

Abbreviations: cm, centimeters.

The results presented in Table 7 are only valid if examining a large amount of data, e.g., on a group level. Considering the large variation observed in the software calculations, our results make it clear that one cannot rely on the software calculations to be reliable if examining individual changes in jump height. It appears as the software agree better for CMJ analysis, slightly worse for SJ analysis, and not at all for DJ analysis. Thus, especially for DJ assessments, different software cannot be used interchangeably, and one should avoid analyzing DJs from software where box height has been used to estimate drop height.

Practitioners that rely on the software calculations should be critical when evaluating the results. Even though our findings did not confirm that large variability in body weight singlehandedly explained the large TEEs% in the software calculations, one should aim to minimize the variability in measured body weight during jump testing protocols.

Practitioners could easily ensure that the body weight does not show variability > 0.1%, by simply checking the body weight which has been reported by the software. Future studies are strongly encouraged to provide force plate users (and software engineers) with direct guidelines on how to minimize body weight variability, both during the jump test protocol and calculation procedures.

Several different force platform systems are commonly used interchangeably both in testing and research facilities. Our results highlight the crucial importance of being aware of the agreement between different test equipment. One should not expect different force platform systems to yield similar results across training, testing, and research facilities. The agreement, or lack thereof, between force platform systems, needs to be accounted for when comparing test results measured by different force platform systems.

Limitations

The findings from this study cannot be interpreted fully without accounting for its limitations.

To investigate concurrent validity, we choose to place the portable force platforms on top of the in-ground reference force platform. Even though we deem this as the best of two alternatives (the other being performing the jumps on the different force platforms in a randomized order (Buckthorpe et al., 2012; Raymond et al., 2018)), this approach is not without limitations. The in-ground force platform was not constructed to measure force with a portable force platform placed on top of it. Consequently, the measures obtained from the in-ground force platform could have been affected by the setup, as the portable force platforms were likely to shake/move slightly when jumped upon. However, when our reference force platform was compared to the CoM model, a better agreement was found than with those of the proprietary software calculations. These findings indicate that the disturbances from the setup *per se* were very minor or neglectable.

Jump height was the only performance variable analyzed in this study. There are reasons to believe that the observed differences between force platform systems would differ for other commonly extracted strategy-related variables obtained from jump testing, e.g., power measures or rate of force development, especially since the peak and average force measures differed in the force platform systems. The results from this study should therefore not be extrapolated to e.g., rate of force development and mean and peak power that are commonly extracted from vertical jump tests (Eagles et al., 2015; Bishop et al., 2021).

What has been defined as Hardware analysis in this study, is not solely reflected in the difference in the hardware. The observed differences are dependent on the calculation procedures used in this study (that is, our reference calculation). We did, however, try to elucidate this during the discussion and we believe that our approach still offers valuable insight into different force platform systems, regardless of their software.

A major limitation to the Software analysis is that we cannot conclude that the reference calculation was superior to the proprietary software calculations. However, the fact that the reference calculation showed smaller variations in the Hardware analysis, indicates how it is unlikely that the reference calculation caused the large TEEs% in the Software analysis. Moreover, all the software agreed with equal tendencies to our CoM model, or in fact slightly worse, while our reference calculation agreed better (Figures 10, 11, 12, and 13), indicating how it was in fact the proprietary software calculations causing the random discrepancies in the Software analysis.

It is also important to mention that even though the CMJs, SJs, and DJs were performed under the same instructions on all force platform systems, the actual jump executions did vary. Individual, biological variations were probably the main cause, but some variation was caused by different constraints in the proprietary software. To exemplify, as stated in the discussion, the MuscleLab software only approved the DJs if the participants landed on the force platform and came to a still position within 1 s. The HurLabs system declined large portions of the DJ executions, where only the preferred DJs were approved on a regular basis. Moreover, some software programs were stricter than others in approving e.g., SJs, and they employed different criteria to approve the jumps. However, we do not believe this affected our results.

No two force platforms should be expected to be alike, even if from the same manufacturer. We cannot know for sure that the force platforms we tested in fact were representative for the specific model from each manufacturer. The reader should be aware of this when translating the findings of this study to their own force platform system.

At last, we tested only a few of a large number of commercially available force platform systems (four out of ~ 15 commonly reported), and the results should be interpreted accordingly. However, in view of the variety of the included force platforms (different sizes, single vs. dual, extension frames vs. not, different sampling frequencies, and different force transducer technologies) we do believe they are representative of the commercially available force platform systems.

Conclusions

In the present study, jump height differed when measured by different commercial force platform systems by 0.1% to 11.6%. The jump height differences were attributed to both data processing algorithms ("software") and hardware (using the same data processing algorithms). The differences in hardware were mostly systematic, with minor random discrepancies (1% to 5%). However, from our results, jump height could differ by ~ 2 cm, even when testing the same jump and applying the same data processing algorithm. For the software calculations, the systematic differences were small, though the random discrepancies were larger than the differences due to hardware (3% to 22%). Different commercially available software differed from each other by up to 3 cm. The results of this study are useful to understand and interpret jump height measured from different commercial force platform suppliers.

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Appendix I

Nomenclature and Definition of Terms

Acceleration: The rate of change in velocity over time, measured in meters per second squared ($m \cdot s^{-2}$).

Accuracy: To what extent the test results (jump height) conform with the correct value or a given standard. In this thesis, accurate measurements entail both reliable and valid measures.

Capacitance: The electrical charge divided by voltage:

$$C = \frac{Q}{V} \tag{A.1}$$

where C represents the capacitance, Q represents the electrical charge, and V represents the voltage.

Concurrent validity: A type of criterion validity where two measurement systems are evaluated concurrently. Usually, an alternative measurement system is evaluated against the accepted gold standard.

Countermovement jump: Bilateral jump performed with a preliminary countermovement.

Current leakage: An electrical current in an unwanted conductive path under normal operating conditions.

Displacement: The change in position of an object. Here referred to as the change in the vertical position of the center of mass.

Drop jump: Bilateral jump performed from a box at a given height. The person drops off the box onto the force plate and jumps for maximal height.

Electrical charge: A charge (positive, negative, or zero).

Electrical circuit: A path that transmits electrical charge.

Error: An incorrect outcome value, which can be attributed to both noise, and e.g., method choices.

Force: The action of a body on another body. It is the action that causes an object to accelerate (Newton's 2nd law).

Force platform: A device that records the ground reaction forces.

Full-scale output: The highest possible input value that can be applied to the force transducers without causing larger measurement inaccuracy.

Gravitational acceleration: The acceleration of a body in free fall. Represented as the letter g in this thesis, which has a value of 9.81 $m \cdot s^{-2}$.
Ground reaction force: According to Newton's 3rd law, to every action, there will be an equal and oppositely directed reaction. The ground reaction force (GRF) is the force exerted by the ground on a body that is in contact with the ground. For example, when a person stands still on the ground, the GRF is equivalent to the person's weight.
Impulse: The integral (accumulation) of force over time.
Kinematics: Describes the motion of bodies, without considering the force which causes the motion.
Kinetic energy: The energy that an object has due to its motion.
Kinetics: Describes the causes of the motion, i.e., the forces involved in causing a movement.
Load: Weight to be carried. In this thesis, load is mostly used to represent known weights placed on the force platform during static testing.
Mass: The quantity of matter in a physical body and its inertia. Measured in kilogram.
Mechanical strain: Deformation representing the relative displacement between two points in a given material.
Noise: Unwanted irregularities in the signal, which are unrelated to the process being measured.
Ohm's law: A law stating the linear relationship between voltage, current, and resistance in an electrical circuit.
Pearson product-moment correlation: A measure of the strength of a linear relationship.
Piezo coefficient: Represented as the charge unit per unit force, or as the voltage gradient per unit of applied pressure.
Potential energy: The energy which is stored in an object due to its position.
Quality: The force transducer's ability to transform the applied force into voltage.
Reliability: The reproducibility of the measurements when they are repeated over time.
Shear stress: Stress which acts coplanar to the cross-section of a respective material.
Squat jump: Bilateral jump performed from a squat position, without a preliminary countermovement.
Validity: To what extent the measurement instrument is measuring what it is intended to measure.
Vector: A value with both a magnitude and a direction.
Velocity: The rate of change of position of a body. A vector quantity, oppositely to speed.

Voltage: Potential energy between electrical charges, or the pressure which makes electricity flow.

Wheatstone bridge: A balanced bridge circuit used to measure small changes in electrical resistance. It consists of three resistors, with known resistance, of which one resistor is adjustable and is used to “balance” the bridge.

Weight: Mass × gravitational acceleration. Measured in newtons.

Appendix II

Natural Frequency

The natural frequency was tested using an accelerometer (BiosignalPlux v.3.0, Lisboa, Portugal) which was taped in the middle of each of the included force platforms. A rubber mallet was used to strike the force platform. We aimed to strike close to the accelerometer—i.e., roughly around the center of the force platform. Three strikes were recorded on each force platform, where one of these was further analyzed. The frequency response was recorded through BiosignalPlux software v.1.0.

The natural frequency was calculated by dividing the number of cycles by the time between these cycles. For the in-ground force platform, 10 cycles were used for this procedure.

The calculated natural frequency of the in-ground force platform was 357 Hz, which is lower than what is reported by the manufacturer (1000 Hz). These findings are in agreement with previous research. As an example, natural frequencies between 288 and 743 Hz have been reported for force platforms where their quoted natural frequency was said to be at least 850 Hz. Similarly, a natural frequency of only 135.8 Hz, has been reported experimentally whereas the quoted natural frequency of that force platform was approximately 800 Hz (Psycharakis & Miller, 2006).

Due to the noise associated with the portable force platforms (they were not anchored to the ground) it was not possible to discriminate between the frequency response of the force platform and the noise, which becomes evident in Figure A1. In Figure A1, an example from one in-ground force platform, and two portable force platform systems is given.

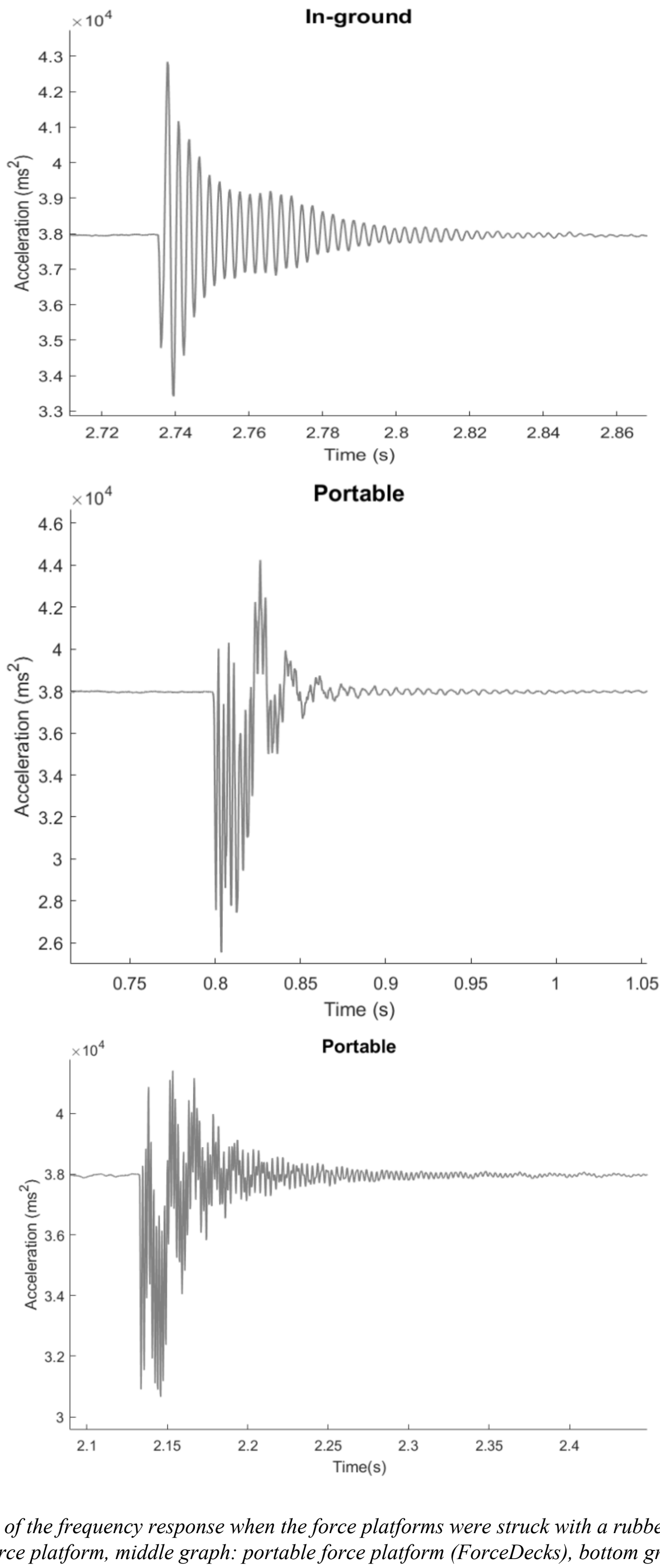

Figure A1. *Example of the frequency response when the force platforms were struck with a rubber mallet. Top graph: In-ground, reference force platform, middle graph: portable force platform (ForceDecks), bottom graph: portable force platform (MuscleLab). Similar observations were observed for the Kistler and HurLabs force platforms. The frequency response is illustrated as the acceleration (ms^2) over time (s).*