Biomechanical Assessment of Countermovement Jumping Using Wearable Technologies

by

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Abstract

Monitoring and assessing physical performance, muscular fitness, and neuromuscular function are essential since they can help to reduce sports-related injuries, improve rehabilitation progress and develop more effective training strategies. Countermovement vertical jump (CMJ) is one of the frequently used means to practically monitor and assess athletic performance in athletic and non-athletic individuals. Previously, force-plate and motion-capture cameras were used in the lab to analyze CMJ-related parameters, including jump height, the main parameter describing the CMJ performance. Although these systems are accurate and precise, their application is time-consuming, expensive, and may not be practical outside of the lab environment. Vertec and jump mat are among the most used instruments to analyze the CMJ-related parameters in the field; however, they have limited precision, and their accuracy was questioned. Despite the potential of inertial measurement units (IMU) for estimating the CMJ-related parameters, their accuracy for this purpose has not been validated.

The objective of this study was to investigate the accuracy and precision of a sacrum-mounted IMU to estimate the spatiotemporal parameters characterizing CMJ against both force-plate and motion-capture cameras as reference criteria during CMJs with and without arms swing. To this end, eleven adults without physical impairments performed six jumps each (four pre-exercise and two post-exercise) on a force-plate while an IMU was placed on the sacrum, and motion-capture system markers were placed on selected anatomical landmarks.

First, the accuracy of the sacrum-mounted IMU to estimate the flight duration, jump duration and jump height during CMJ with and without arms swing was investigated. For the flight and jump duration, the mean errors (standard deviation) were 0.06 (0.17) sec and -0.03 (0.20) sec, respectively, for the CMJ with arms swing and 0.16 (0.22) sec and -0.07 (0.24) sec, respectively, for the CMJ without arms swing. Compared to both the force-plate and motion-capture system, the error of jump height estimated by the IMU was relatively small during the CMJ with and without arms swing. These errors were comparable to the difference between the jump height obtained by the force-plate and motion-capture system. Also, statistical correlations were observed between the jump height obtained by these three measurement systems. Flight duration, jump duration, and jump height obtained by IMU compared to force-plate showed that the IMU could not be used as a substitute for force-plate. Yet, errors in IMU measurements compared to force-plate were similar to the ones observed in motion-capture system. As a result, further studies might be conveyed to reduce the error of IMU compared to the force-plate. Second, the accuracy of the sacrum-mounted IMU in estimating flight-time to contraction-time (FT:CT) ratio and change was investigated. The relative mean error (standard deviation) of FT:CT ratio estimated using the IMU against the force-plate was 11.7% (13.3%) and 23.2% (11.7%) for CMJs with and without arms swing, respectively. The relative mean error (standard deviation) of change in FT:CT estimated using the sacrum-mounted against to force-plate was 7.6% (16.8%) and 9.5% (25.3%) for the CMJs with and without arms swing, respectively. Similarly, the IMU could not be used as a substitute for force-plate. Yet, further studies are needed to decrease the IMU error and investigate the IMU's potential to detect neuromuscular fatigue.

Preface

This thesis is an original work by Ramin Fathian. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Biomechanical Assessment of Vertical Jumping Using Wearable Technologies.", No. Pro00085074.

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Dedicated to

My Parents; Hasan and Rozita

and

My little sister, Azin

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1 Introduction

1.1 Countermovement Jump and Applications

Monitoring and assessing physical performance, muscular fitness, and neuromuscular function can help reduce sports-related injuries, improve rehabilitation progress and increase efficacy of training plans. One of the frequently used means to assess and monitor physical performance, muscular fitness, and neuromuscular function is the vertical jump test (Malliou et al., 2003; McMahon et al., 2018a; Wisløff et al., 2004). Vertical jump includes different categories such as; drop, rebound-continuous, squat, and countermovement jump (CMJ). Among different modes of the vertical jump, the CMJ is the most frequently used since it is simple and close to movements made during a wide range of athletic activities.

Parameters characterizing the vertical jump, including the temporal and spatial parameters (e.g., jump height, flight time), have been the topic of several research studies since these parameters were shown to be statistically correlated with the physical performance of athletes (Barr and Nolte, 2011; Hudgins et al., 2013; Thomas et al., 2017; Weinert-Aplin et al., 2017). Force-plate and motion-capture systems are known as reference measurement systems available in human motion laboratories and used for studying a variety of motions, including vertical jump (Windolf et al., 2008a). Despite the accuracy and reliability of the force-plate and motion-capture system, their application is expensive, time-intensive, and limited to a dedicated lab environment. Despite force-plate and motion-capture systems, Vertec and jump mats are relatively inexpensive and user-friendly devices used to estimate jump height and flight-time. Yet, their precision is limited, and their validity has been questioned (Peterson et al., 2015).

Wearable inertia measurement units (IMU) capable of measuring three dimensional (3D) acceleration and angular velocity. IMU has been used in a variety of environments such as medical rehabilitation, robotics, navigation, virtual reality and sports learning (Ahmad et al., 2013; Mariani et al., 2013; Najafi et al., 2015; Rouhani et al., 2011, 2010; Salarian et al., 2007). The promising outcomes of the IMUs in several applications motivate us to investigate their accuracy and validity as a portable, inexpensive, compact, and precise estimator of CMJ parameters.

1.2 Thesis Objectives

The main objective of this study was to investigate the validity of sacrum-mounted IMU against the force-plate and motion-capture systems as reference methods to estimate the temporal and spatial parameters characterizing the CMJ with arms and without arms swings. To pursue this objective, an experimental study including the following activities was performed for eleven study participants: (i) two CMJ with arms swing, (ii) two CMJ without arms swing, (iii) one post-exercise CMJ with and without arms swing. Then, we measured the CMJ parameters using a force-plate, a motion-capture system, and an IMU, and validated the accuracy of the latter versus the two others.

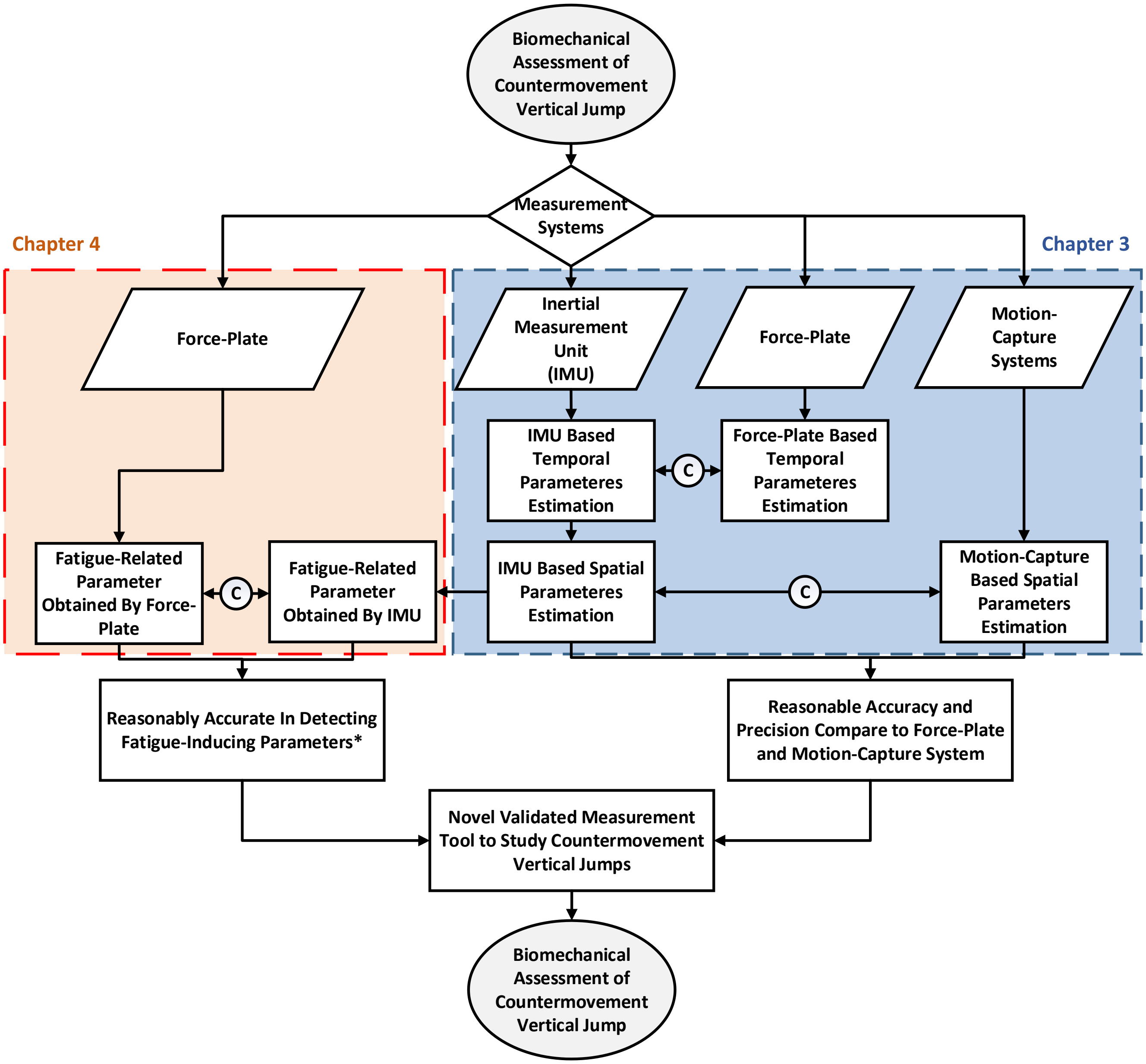

Figure 1 The thesis structure

1.3 Thesis Outline

This thesis is structured as follows (**Figure 1**). In Chapter 2, a review of the literature related to the performance assessment based on the CMJ, analysis of biomechanical quantities during CMJ, wearable sensors for human movement analysis, and neuromuscular fatigue are presented.

Chapter 3 presents the detection of key time instants (beginning of the jump, take-off, touch-down, end of the landing) during a CMJ and estimation of the CMJ height using a sacrum-mounted IMU. The validity of our proposed method is investigated against force-plate and motion-capture systems. Chapter 4 presents the effect of neuromuscular fatigue on the spatial and temporal parameters of the CMJ based on a comparison between the pre- and post fatigue measured parameters. In Chapter 5, a summary of the findings, key remarks on the performed study, discussion and future perspectives are presented.

2 Literature Review

The vertical jump is described as an act of propelling the body into the air and getting off the ground (Offenbacher, 1970), and has different modes: countermovement, squat, drop, rebound-continuous jump (**Figure 2**). Developments in the fields of piezoelectric elements, strain gauges, and beam load cells led to the appearance of commercial force-plates (Bertram, 2016; Jenkins, 2005) that established the basis of human locomotion as well as vertical jumping analysis (Bosco and Komi, 1980; Cavagna et al., 1971; Komi et al., 1974).

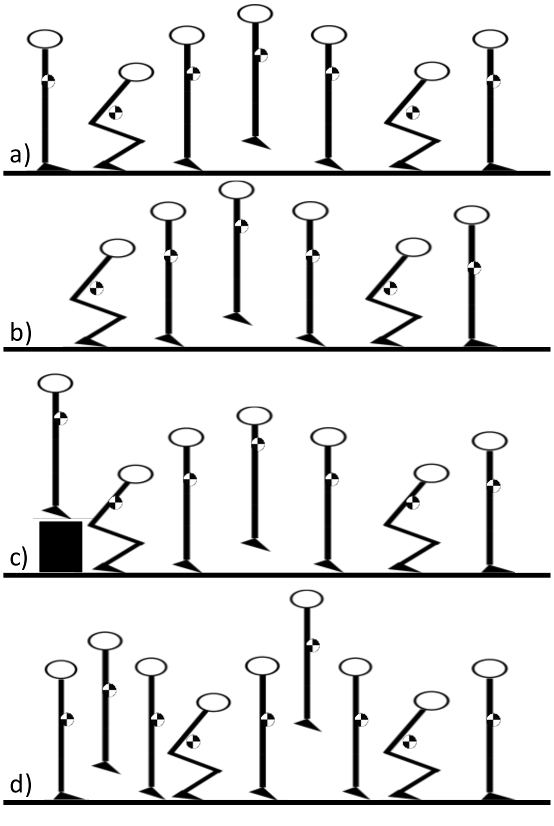

Figure 2 Different modes of vertical jumping, a) Countermovement Jump, b) Squat jump, c) Drop jump, d) Rebound-continuous jump

Out of different modes of vertical jumping, CMJ has been used in literature as a measure to assess the physical performance. Studies in recent years have shown that analysis of CMJ phases individually, as well as the entire CMJ, provide valuable insight into lower limb strength and neuromuscular function (Cormie et al., 2009; Gathercole et al., 2015; Laffaye et al., 2014; McMahon et al., 2017; Rice et al., 2017; Sole et al., 2018).

2.1 Countermovement Jump (CMJ)

2.1.1 CMJ Phases

The CMJ starts with an upright standing position (quiet standing) followed by a countermovement (squatting down) at which the ankle, knees and hips flex. Then, an extension in the knee and hip joints causes propulsion vertically into the air. Different methods have been described in the literature to separate the CMJ. McMahon et al. (2018b) presented quiet standing (weighing), squatting down (unweighting), braking, propulsion, flight, and landing as key phases of the CMJ (contraction time consists of squatting down, braking and propulsion phases) (**Figure 3**). These phases have been selected based on the force exerted by the lower limb to the ground. During the quiet standing phase, the vertical force applied to the ground is equal to the weight of the individual. In the second phase (squatting down), the vertical force decreases as the jumper relaxes agonist muscles, which cause flexion in the knee and hip joints. Then, in the braking and propulsion phases, knee flexors activate and lead to taking off the ground and the beginning of the flight phase (Linthorne, 2001; McMahon et al., 2018a; Walsh et al., 2012). An alternative to this method is dividing the CMJ into unloading and loading phases. This terminology is easier to interpret as the intervals, in which the vertical force is lower and higher than the jumper’s body weight, are considered as unloading and loading, respectively. Based on this method, the CMJ starts with the unloading phase followed by the loading phase, which leads to take-off.

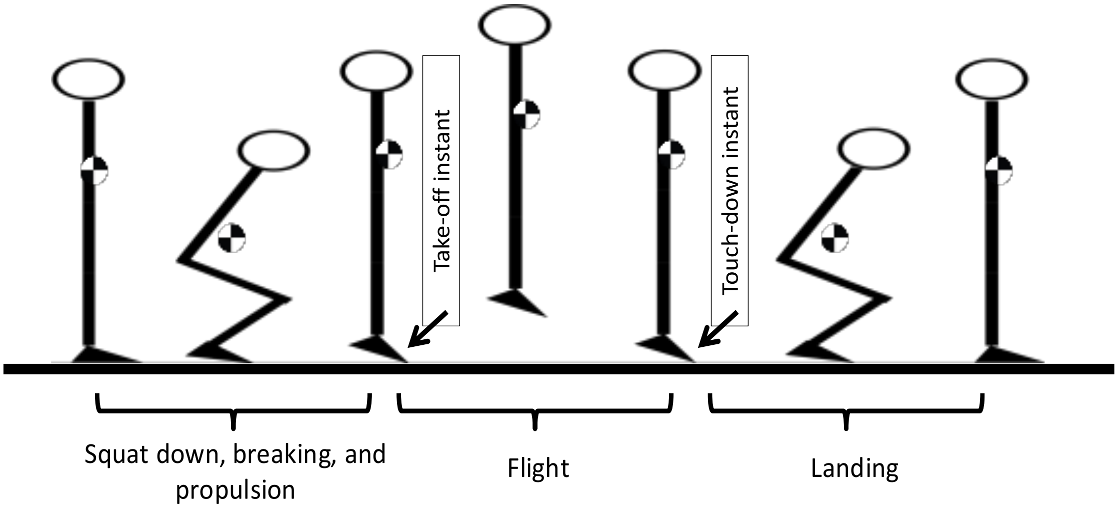

Figure 3 Squat down, breaking, propulsion, flight, and landing phases as well as take-off and touch-down instants during CMJ

2.2 Assessment of CMJ

A variety of apparatus have been used to study spatiotemporal parameters of vertical jump, more specifically, CMJ. Vertec, jump mat, motion-capture systems, force-plate, and IMU are the ones seen in a variety of studies (L. Z. F. Chiu and Dæhlin, 2019; Innocenti et al., 2006; Leard et al., 2007; Moir, 2008; Picerno et al., 2011; Setuain et al., 2015).

2.2.1 Vertec

Vertec (**Figure 4**) measure the jump and reach height which could be translated to jump height. The jump height will be defined as the difference between the height of the highest displaced vane and the jumper reach height. Vertec is a relatively inexpensive and user-friendly device to use as a means to measure the jump height for a variety of jump modes. Yet, its application may be limited to the lab or gym environment, it has limited accuracy, and its validity has been questioned (Peterson et al., 2015). The quantized nature of the jump height measurement using Vertec, uncertainty in measuring jumper reach height, the effect of floor surface condition and forwards, backwards, and sideways displacement during the vertical jump are the sources of error when Vertec is used.

Figure 4 Commercial Vertec (ROGUE Fitness, USA) used for estimation of vertical jump height based on the highest displace vane (adapted from: https://www.elitefts.com/powermax-vertec-jump-measuring-device.html)

2.2.2 Jump mat

The jump mat (**Figure 5**) is another relatively inexpensive and user-friendly device to be used for estimation of jump height. Jump mat measures the duration in which the jumper’s feet are not in contact with the mat. This durtaion is considered as the flight time. The jump height obtained from the jump mat is estimated using the flight time calculated by having the take-off instant, touch-down instant, and ballistic equation. Despite being an inexpensive and user-friendly device, jump mat accuracy and precision are limited, and its validity has been questioned. Moreover, the jump height estimated using the jump mat represents the maximum centre of mass (COM) displacement during the flight time from take-off instant (**Figure 6**).

Figure 5 Jump mat (Power Systems, USA) used for vertical jump height estimation (adapted from: https://www.power-systems.com/shop/product/just-jump)

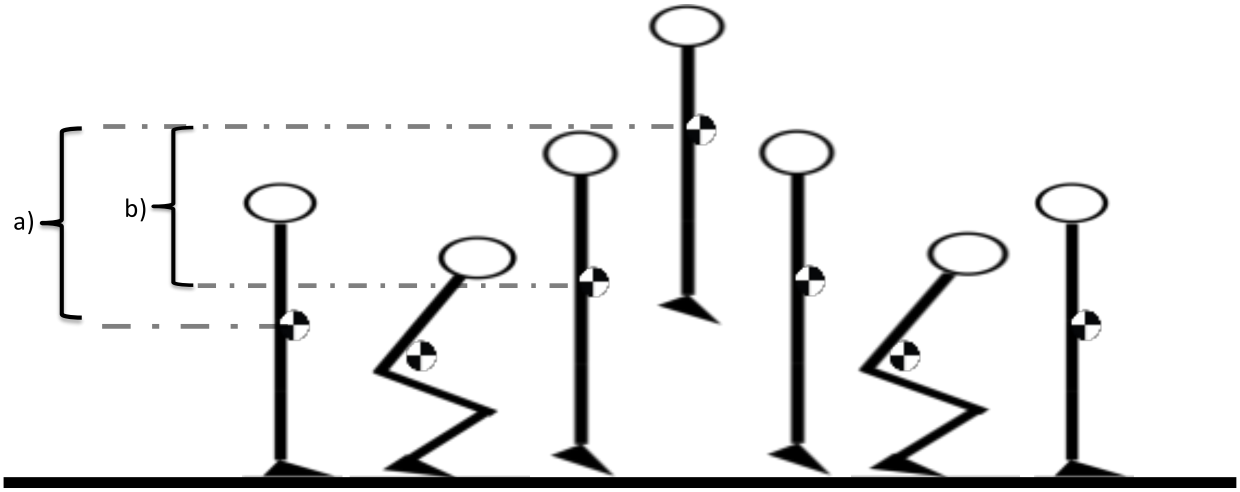

Figure 6 Definitions of jump height; a) maximum COM displacement from quiet standing, b) maximum displacement of COM from take-off instant

2.2.3 Motion-capture system

The 3D motion-capture systems, especially the optoelectronic stereophotogrammetric systems, have been widely used in human movement studies to instantaneously triangulate the 3D position of markers attached to the human body. Active and retroreflective passive markers are two types of markers used in the motion-capture systems. Active markers dim sequential pulses, which are trackable by the motion-capture system (Leardini et al., 2005). Passive markers need to be used in combination with cameras equipped with light-emitting diodes illuminating infrared light (Ferrigno et al., 1990; Leardini et al., 2005; Taylor et al., 1982; van der Kruk and Reijne, 2018). For studying the movement of any rigid body, having the kinematics of at least three non-aligned points of the rigid body is needed. Similarly, at least three non-collinear markers are needed on each body segment together with simultaneous visibility by two or more motion-capture cameras (Cappozzo et al., 2005). Pattern recognition software, along with the motion-capture cameras and markers, is needed to triangulate and reconstruct the 3D position of each marker.

Having an instantaneous 3D position and orientation of body segments along with the anthropometric data of the human body enables estimation of the body COM position during any human movement (Winter, 2009). Similarly, estimation of the instantaneous position of body COM during CMJ is possible by placing the markers on the landmarks introduced in the literature (Dumas et al., 2007; Mass et al., 2012; Tisserand et al., 2016; Winter, 2009). Knowing each segment's weight normalized to body weight, the segment's COM of normalized to segment length and trajectory of markers placed on the two ends of the segments along with considering the human body as multi-segment system, enable estimation of the human body COM.

Although motion-capture systems are able to measure the body segments' movements, their use is subject to disadvantages, mainly being time-intensive. A significant amount of time is needed for participant preparation, anatomical landmark detection, markers placement, fixture, and post-processing of recorded data. In addition, motion-capture systems are expensive and require a dedicated laboratory space and a trained operator to conduct the study (van der Kruk and Reijne, 2018).

Similar to any measurement system, the motion-capture systems are subject to several sources of error (Cappozzo et al., 2005; Chiari et al., 2005). Instrumental errors, soft tissue artifact, and landmark misplacement are the main sources of error that may affect the 3D position measurement using motion-capture systems. The instrumental error includes errors caused by inaccuracies in the calibration process, electronic noise, missing markers, and marker flickering (Chiari et al., 2005). Another source of error is soft tissue artifacts caused by the relative movement of the skin-mounted markers with respect to the underlying bones considered as landmarks. These relative movements are mostly caused by muscle contraction and segment motion (Stagni et al., 2005). The inaccuracy caused by soft tissue artifacts is typically larger than the instrumental errors (Leardini et al., 2005). Marker misplacement on the landmark due to the misdetection of landmarks is another source of error (Croce et al., 2005). This error may vary among individuals with different conditions. For example, large errors are caused by soft tissue artifacts and marker misplacement for individuals with obesity.

2.2.4 Force-plate

The force-plate is among the most used devices in human biomechanics research, designed to measure the ground reaction force, the centre of pressure, and the free frictional moment applied to its surface. The force-plate has been widely used in the analysis of athletic activities such as vertical jump, including CMJ, squat jump, and rebound jump (L. Z. F. Chiu and Dæhlin, 2019; Hatze, 1998; Kibele, 1998; Street et al., 2001a).

Over the years, several force-plate based methods have been developed to assess the vertical jump height as the essential parameter in assessing vertical jump performance. In these methods, one or a combination of the estimated flight-time, vertical velocity of the COM at the take-off instant, and the COM at the take-off instant were used to estimate the jump height. (Aragón-Vargas, 2000; L. Z. F. Chiu and Dæhlin, 2019; Hatze, 1998; Linthorne, 2001; Moir, 2008; Shetty and Etnyre, 1989; Sole et al., 2018).

Flight time (FT) method: This method works based on the ballistic equation (equation 2-1) where g is gravitational acceleration and t is flight time (the period between the take-off instant and touch-down instant). Take-off and touch-down instant are detected applying thresholding techniques to the vertical component of the force measured by force-plate. Different thresholds and digital filters have been introduced for accurate and reliable estimation of jump height, which are mostly multipliers of the residual force recorded during the flight time. By definition, the jump height is the vertical displacement of the COM from the quiet standing to the jump apex (James et al., 1993; Vanrenterghem et al., 2001). Yet, the flight time method measures the vertical displacement of the COM from the take-off instant to the apex of the jump. Ignoring the vertical displacement of the COM from the quiet standing to the take-off instant may cause inaccuracies in estimating jump height (L. Z. F. Chiu and Dæhlin, 2019). This method is also subject to errors that are caused by inaccuracies in the selection of g value and selection of a threshold for detecting take-off instant.

$$Vertical\ jump\ height = 0.5g(t/2)^2 \qquad \text{2-1)}$$

Take-off velocity (TOV) method: In this method, the vertical velocity at the take-off instant is calculated by integrating the net vertical force applied to the jumper prior to take-off instant (equation 2-2) where g is gravitational acceleration, $F_{vertical}$ is vertical component of force measured by the force-plate, dt is sampling duration, F_w is body weight of the jumper, and F_o is the offset on force-plate signal during flight time. The TOV method also measures the difference in vertical position of the body COM at the take-off instant compared to the apex of the jump, and thus, is subject to errors, similar to the FT method. Sources of inaccuracies are the filtering, inaccuracies in the selection of g value, sample duration, integration technique, detecting the initiation time and take-off time, F_w,and F_o. These sources of error cannot be eliminated; yet, their effect can be minimized. Vanrenterghem et al. (2001) investigated the effect of sampling duration and Simpson's rule for integration. The range defined by a maximum of vertical force during 2 sec of quiet standing added to its standard deviation and the minimum of vertical force during the 2 sec of quiet standing subtracted by its standard deviation was suggested for detecting the initiation time. Averaging the vertical force over 0.5 sec was introduced for estimating the body weight. Additionally, a threshold of 10 N on the raw recording of the force-plate was suggested to detect the take-off time. In another study, Street et al. (2001a) suggested 1.75 times the residual force found during the 2 sec of quiet standing as a threshold for detection initiation time. The maximum residual force during 0.4 sec added to the smallest standard deviation of 0.4 sec moving window during the flight time was suggested for estimating force-plate signal offset during the flight time (this offset should be removed). The average of the vertical force over 2 sec of quiet standing was used for estimating body weight.

$$Vertical\ jump\ height = 0.5g\left(\frac{\int_{initiarion\ time}^{take-off\ time}(F_{vertical} - F_w)dt}{F_w - F_o}\right)^2 \qquad 2\text{-}2)$$

Take-off velocity plus height at take-off instant (TOVH) method: Both FT and TOV methods estimate the difference in vertical position of the body COM at the take-off instant compared to that at the apex of the jump. The presented jump height may not be equal to the actual vertical jump height (**Figure 6**) due to foot plantar flexion and arms swing. In the TOVH method, the height at the instant of take-off time is added to the height estimated by the velocity at the take-off instant to obtain the jump height. The height at the take-off time instant is calculated by double integrating the net vertical force applied to the jumper from the initiation time to the take-off time. Approximately 2-4 cm increase in the vertical jump height following exercise interventions is reported (Bloomquist et al., 2013; Hartmann et al., 2012). Ignoring the height at the take-off instant was reported to produce 1.8 cm and 2.1 cm of error (in male and female jumpers, respectively) in the estimated jump height (Bloomquist et al., 2013; Hartmann et al., 2012), which may affect the characterization of improvements in vertical jump height (L. Z. F. Chiu and Dæhlin, 2019; Moir, 2008). Based on the literature, the TOVH method is the most reliable and recommended method for measuring vertical jump height using the force-plate.

2.2.5 Inertial Measurement Unit (IMU)

In recent years, the IMU has been used to assess human body movement such as monitoring daily activities, gait analysis (Aminian et al., 2002; Najafi et al., 2003; Rouhani et al., 2014; Salarian et al., 2004), and gesture detection (Kundu et al., 2018; Varkey et al., 2012). These wearable sensors consist of 3D accelerometer, 3D gyroscope, and sometimes 3D magnetometer which measure the 3D acceleration, 3D angular velocity, and strength of magnetic field. They are lightweight, low-cost, and user-friendly. Their use is not limited to the lab environment. The application of IMUs has facilitated ambulatory health monitoring and human performance assessment.

IMU-based methods for CMJ assessment have mostly been based on the flight time estimation using a single IMU mounted on the ankle, the shank, torso, or sacrum (Palma et al., 2008; Quagliarella et al., 2010; Rantalainen et al., 2018a). In addition to the flight-time based methods, methods based on take-off velocity and double integration of vertical acceleration were suggested in some studies (Innocenti et al., 2006; Picerno et al., 2011; Rantalainen et al., 2018a).

Rantalainen et al. (2018a) investigated the validity of jump height estimated based on the FT method and TOV method obtained from an IMU mounted on the torso. The validity of these IMU-based methods was compared to the measurements of the force-plate. In these IMU-based methods, in addition to ignoring the vertical position at the take-off instant compared to quiet standing, the acceleration caused by the rotational motion of IMU mounted on the torso may cause inaccuracies in measurement.

Picerno et al. (2011) studied a sacrum-mounted IMU to estimate jump height using a free-fall motion equation.

$$H_{(t)} = H_o + v_0 + 0.5g(t)^2 \qquad (2\text{-}3)$$

where $H_o \text{ and } v_0$ are the height and vertical velocity of the COM at the take-off instant calculated double-integrating and integrating vertical acceleration, respectively. Flight time (t) was defined as the duration in which the vertical acceleration measured by the IMU was determined to be equal to or lower than the gravitational acceleration (g). Although the accuracy of this method was validated against the motion-capture system, little information was provided about the experimental setup and the markers used. Indeed, the marker-set used for the motion capture system as a reference could affect the validation results. Additionally, the accuracy of the proposed method relied on the flight time detection, which could be subject to inaccuracy.

In summary, the literature review revealed that the assessment of CMJ using a single IMU is not adequately studied. First, there is no comprehensive study that investigated the accuracy of spatiotemporal parameters of CMJ jump, including jump height and time instants estimated using a single IMU mounted on the sacrum against the force-plate and motion-capture system. Second, no method based on double integration of the corrected accelerometer recording is presented in the literature for jump height estimation. As a result, no reliable in-field method is available for accurate assessment of CMJ using an IMU.

3 Assessment of Countermovement Jump with and without Arms Swing Using a Single Inertial Measurement Unit

3.1 Introduction

Vertical jump height has been a primary means to monitor and assess the muscular fitness and neuromuscular function in healthy, injured, athletic, and non-athletic individuals (Malliou et al., 2003; McMahon et al., 2016; Wisløff et al., 2004). Measuring vertical jump height paves the way toward having a better understanding of the effectiveness of training and therapeutic approaches.

There are different modes of vertical jumping, including squat, rebound-continuous, drop, and countermovement vertical jumps. Out of these modalities, the countermovement jump is the most commonly used vertical jump to monitor and assess performance because of its convenience and similarity to movements made during a wide range of physical activities and sports. The countermovement jump can be performed with and without arm swing. Force-plate, motion-capture systems, Vertec (used in jump and reach tests), and jump mats (which estimates the jump height based on measured jump flight time) are currently used to estimate vertical jump height. Vertec and jump mat are relatively inexpensive and user-friendly devices, but they have limited precision, and their validity has been questioned (Ferreira et al., 2010). Force-plate and motion-capture cameras are considered as reference criterion because of their accuracy and reliability (Chiu and Dæhlin, 2020; Moir, 2008; Windolf et al., 2008b; Yang et al., 2012). Various approaches have been developed to obtain an accurate jump height using force-plate and motion-capture cameras (Chiu and Dæhlin, 2020; Chiu and Salem, 2010). Yet, they are expensive, and their use is time-consuming and limited to a dedicated lab environment.

Wearable inertial measurement units (IMU) measure three-dimensional (3D) acceleration and angular velocity. The motion of the sacrum may represent motion of the total body COM (Chiu and Salem, 2010; Mapelli et al., 2014; Saini et al., 1998), therefore, the 3D acceleration and 3D angular velocity from a sacrum mounted IMU has potential to be translated into the jump height. Therefore, the IMU can be a portable, inexpensive and precise substitute for existing instruments. More importantly, the application of IMU is not limited to the laboratory environment and can be used for field tests.

Previously, accelerometer and IMU technologies have been used to assess and analyze vertical jumps. In some studies, the flight-time obtained by an IMU mounted on the hip or ankle was used, and criterion validity was compared against either a jump mat or force-plate (Palma et al., 2008; Quagliarella et al., 2010; Rantalainen et al., 2018b). Also, flight-time and take-off velocity obtained from a torso-mounted IMU were separately used to estimate the jump height from the free-fall motion equation and vertical displacement equation, respectively (Rantalainen et al., 2018a). In the mentioned study, the reliability of jump height obtained using these IMU-based methods was compared to that obtained by force-plate. Picerno et al. (2011) used a sacrum-mounted IMU to calculate the take-off velocity and the body COM's height at the instant of take-off based on the integration of the sacrum's acceleration and the free-fall motion equation. Then, the jump height was considered as the summation of the COM's height at take-off instant and the maximum displacement calculated using the free-fall equation. The criterion validity of the method presented by Picerno et al. was investigated against a motion-capture system. Methods based on double-integration of accelerometer readouts were used in previous studies (Innocenti et al., 2006; Picerno et al., 2011). Yet, the effect of pelvis rotation on the accelerometer signal and misplacement of the accelerometer on the sacrum, could both subsequently affect the calculated jump height, were not considered.

In general, the discussed methods for jump height calculation presented errors associated with ignoring the COM height at take-off (L. Z. F. F. Chiu and Dæhlin, 2019) and neglecting pelvic rotation during the jump (Chiu and Salem, 2010). An IMU can be used to estimate jump height via double integration of acceleration, accounting for COM height at take-off. Furthermore, a sacrum mounted IMU can be used to estimate pelvic rotation via integration of angular velocity. Whether an IMU can accurately estimate jump height is dependent on whether the motion of the IMU represents the motion of the body's COM. Therefore, the purpose of this study was to investigate the accuracy of vertical jump height measurement using a sacrum-mounted IMU during countermovement jump with and without arm swing. To this end, we developed algorithms to estimate the flight time and COM trajectory using the IMU and experimentally compared the results to those obtained motion-capture cameras and force-plate as two criterion references.

3.2 Materials and methods

3.2.1 Measurement systems

Three measurement systems were used; IMU, motion-capture cameras, and force-plate. An IMU (MTws, XSENS Technologies, NL) composed of a tri-axial accelerometer and a tri-axial gyroscope, was attached to a rigid plate with a cluster of five retroreflective markers. This module was affixed over the participant’s sacrum via double-sided medical tape to estimate the total body COM trajectory during the countermovement jump (**Figure 7**). The IMU recorded the sacrum’s 3D acceleration and 3D angular velocity at a 100 Hz sampling frequency.

A motion-capture system (VICON, Oxford Metrics Group, UK) with 12 stereophotogrammetric optoelectronic infrared cameras recorded the trajectory of the retroreflective markers, synchronously with the sampling frequency of 100 Hz. Retroreflective markers were attached to the anatomical landmarks (**Figure 7**) of the body in addition to the IMU plate. The motion-capture cameras were used as a reference method to explore the accuracy of IMU tracking the motion of pelvis and the validity of estimating the COM trajectory based on the pelvis motion using IMU.

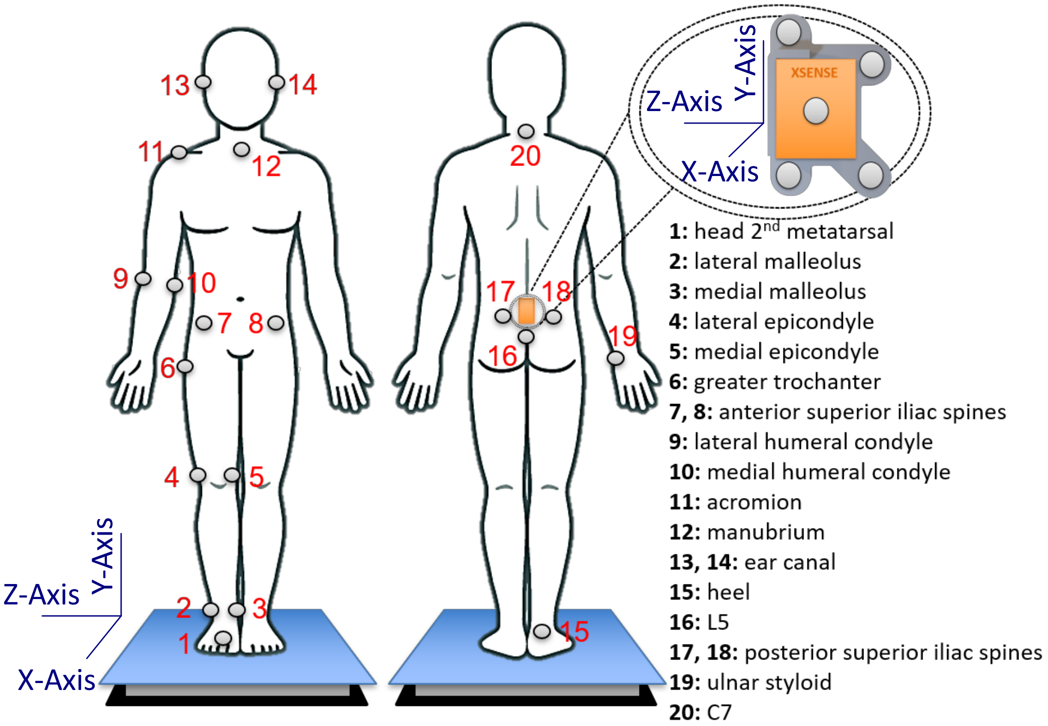

Figure 7 The measurement setup: An IMU placed on the sacrum, reflective markers placed on the IMU plate and on anatomical landmarks of the body. The pelvis' anatomical frame consisted of the x-axis aligned with the anterior direction, y-axis aligned with the upward direction, and z-axis aligned with lateral direction pointing to the right side of the participant.

A force-plate (OR6-7, AMTI, Watertown, MA, USA) was used to record the ground reaction forces at a 1000 Hz sampling frequency, synchronously with the IMU and motion-capture system, while the participant performed countermovement jumps (**Figure 7**). The force-plate was used as a reference system to measure the accuracies of jump height estimation and temporal event detection using the IMU during countermovement jump.

3.2.2 Participants recruitment

Eleven volunteers (all male, age: 27 ± 2, body mass: 74 ± 7 kg, body height: 179 ± 5 cm) participated in the experiment. The experiment procedure was approved by the Research Ethics Board Committee of the University of Alberta (Pro00085074). Participants were asked to read and sign the written informed consent form prior to participating in the experiment. Participants performed four countermovement jumps, two without arms swing and two with arms swing on the force-plate while IMU and reflective markers were attached to their body.

3.2.3 Jump height assessment using IMU

The algorithm to estimate the jump height during countermovement jump using an IMU was based on the double-integration of the body COM acceleration, which required the detection of temporal events during CMJ.

3.2.3.1 Phase 1: Detection of temporal parameters during countermovement jump

Based on previous works (Casartelli et al., 2010; McMahon et al., 2018a; Setuain et al., 2015; Vanrenterghem et al., 2004, 2001), an entire countermovement jump is broken down into the following phases: quiet standing, countermovement (including unweighing, braking, and propulsion), flight, and landing. These four phases are separated by the following time instants: initiation time (t_{in}), take-off time (t_{to}), touch-down time (t_{td}), and landing time (t_{la}). An algorithm was programmed to detect these time instants using the IMU automatically. To validate the accuracy of detecting time instants, the vertical ground reaction force from the force-plate was used as the criterion standard.

The participant's body weight and force-plate signal offset were calculated by averaging the vertical ground reaction force over 1 sec and 0.3 sec periods during the quiet standing and flight phase, respectively (Street et al., 2001; Vanrenterghem et al., 2001; Linthorne, 2001). Five times the standard deviation of body weight during quiet standing was considered as the threshold to define t_{in} and t_{la} (Eagles et al., 2015). Similarly, five times the standard deviation of flight force (after deducting the signal offset recorded by force-plate during the flight time from the original flight force) was considered as a threshold to define t_{to} and t_{td}.

The same time instants were detected using resultant of the acceleration signal from the IMU recording. For this purpose, three times the standard deviation of the resultant of accelerometer signal during one second of the quite standing phase was considered as a threshold to detect the time intervals in which t_{in} and t_{la} happened. Then, the local peaks of the resultant of acceleration signal of the accelerometer were detected as t_{to} and t_{td}.

3.2.3.2 Phase 2: Jump height estimation during countermovement jump

The algorithm to estimate jump height using the IMU involved double integration of vertical acceleration, which required information regarding the orientation of the sacrum mounted IMU. To validate the IMU jump height estimates, both force-plate and motion-capture cameras were used as reference criteria.

3.2.3.2.1 Measurement using IMU

To extract the acceleration of the body COM, we removed the projection of gravitational acceleration in the accelerometer readout using the following steps:

Step 1) Low-pass filtering: The acceleration, and angular velocity signals were filtered using zero-delay 6th-order low-pass Butterworth filter with the cut-off frequency of 40Hz.

Step 2) Finding the pelvis orientation: By knowing the 3D acceleration measured during quiet standing, the sensor-to-segment transform matrix was formed and the 3D acceleration and 3D angular velocity recorded in the IMU-embedded frame (**Figure 8.a, Figure 8.b**) were transferred into the pelvis' anatomical frame (**Figure 8.c, Figure 8.d**) to have a vertical y-axis during quiet standing (Nazarahari et al., 2019). The initiation time (t_{in}) and landing time (t_{la}) were obtained using IMU according to Phase 1 above. The pelvis orientation during the countermovement, flight, and landing phases (**Figure 9.a**) was calculated from strap-down integration of 3D angular velocity (Higham, 2009; Rouhani et al., 2012). The initial orientation was considered the pelvis orientation during the quiet standing phase right before the countermovement phase.

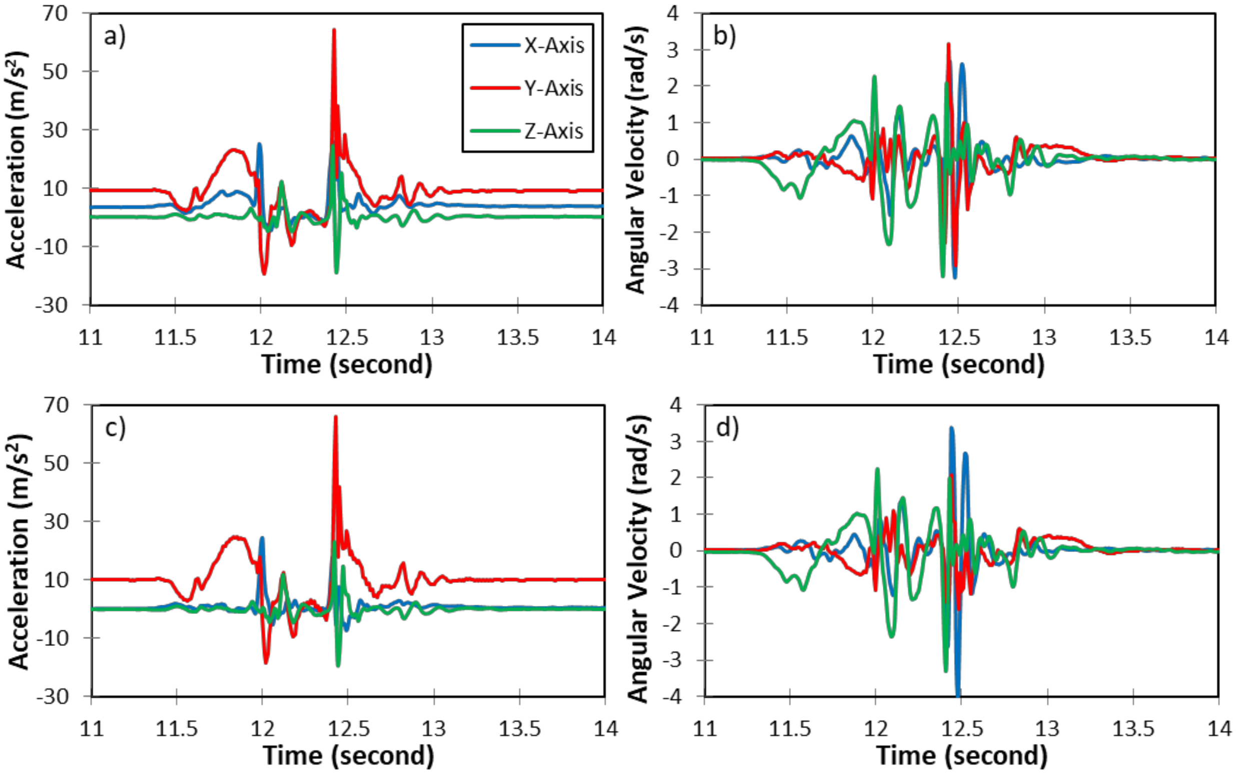

Figure 8 3D acceleration (a) and angular velocity (b) recorded in the IMU-embedded frame, and 3D acceleration (c) and angular velocity (d) of IMU presented in the pelvis' anatomical frame.

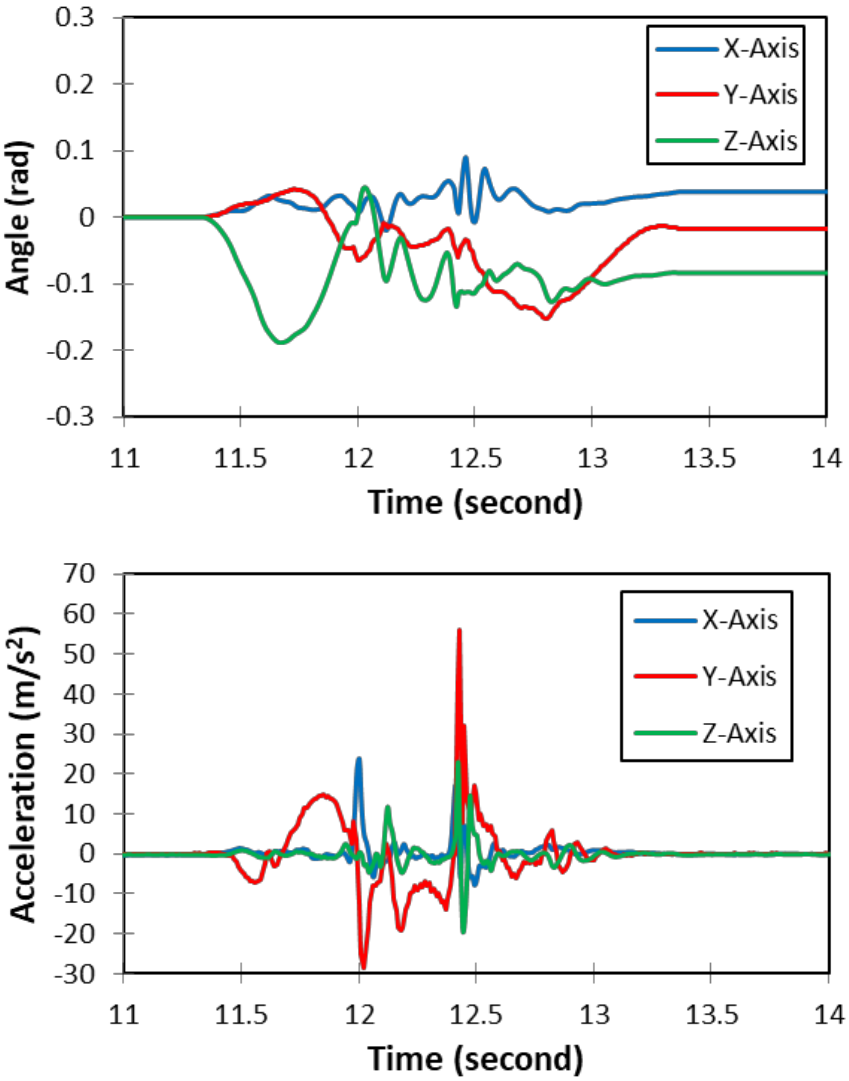

Figure 9 Orientation of the pelvis' anatomical frame expressed as three Euler angles in degree during the CMJ phases, with respect to its initial orientation at the end of quiet standing (a), and the body COM acceleration based on the IMU acceleration presented in the global frame (b). The projection of the gravitational acceleration is removed, knowing the orientation of the pelvis' anatomical frame.

Step 3) Body COM acceleration calculation: Using the pelvis orientation obtained in Step 2, the 3D acceleration of the sacrum measured by the IMU was transferred from the pelvis' anatomical frame into the global frame. Then, the projection of gravitational acceleration was subtracted from the 3D acceleration of sacrum to obtain the 3D COM acceleration (**Figure 9.b**).

Step 4) Body COM trajectory estimation: The COM trajectory was calculated by numerical double-integration of 3D COM acceleration. To minimize the accumulated error in numerical integration, zero velocity correction (**Figure 10.a**) and zero vertical displacements correction (**Figure 10.b**) were applied (Ahmadian et al., 2020): Assuming that COM velocity and displacement are equal to zero at quiet standing phase, the difference between these values in the beginning and end of the entire countermovement jump was considered at the draft. As a result, the velocity and displacement of the sacrum were corrected during the flight phase using piecewise cubic Hermite interpolating polynomial curve fitting of the drift. The maximum COM displacement during the flight phase relative to quiet standing was considered as the jump height.

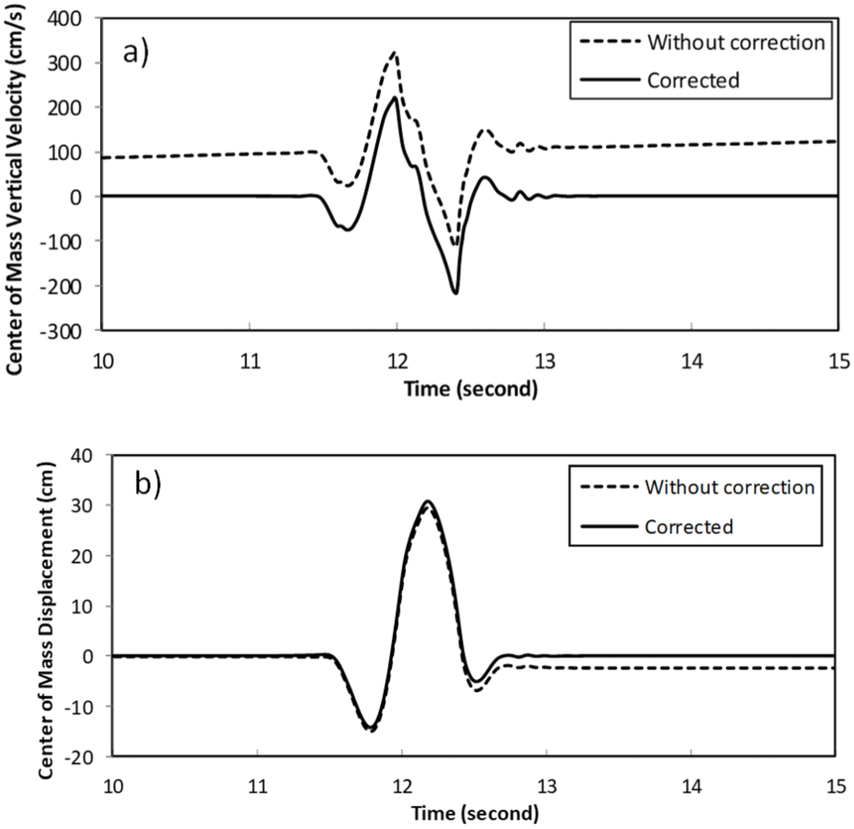

Figure 10 The vertical velocity of the body COM obtained by integration of the vertical acceleration before and after correction (a), and the vertical displacement of the body COM obtained by integration of the corrected the vertical velocity before and after correction (b)

3.2.3.2.2 Measurement using motion-capture cameras

Body COM trajectory was estimated using normative anthropometric data of body segments. The proximal and distal ends of body segments (foot, shank, thigh, pelvis, thorax, head, upper arm, forearm) were identified with retroreflective markers. The COM positions of all the right segments were calculated according to (Winter, 2009), and assuming left-right symmetry, the whole-body COM position was estimated. The jump height was defined as the difference between maximum COM height and its value at the quiet standing phase.

3.2.3.2.3 Measurement using force-plate

The vertical ground reaction force provided by the force-plate platform was filtered using a zero-delay 6th-order low-pass Butterworth filter with the cut-off frequency of 40 Hz (L. Z. F. F. Chiu and Dæhlin, 2019). Then, knowing t_{in} and t_{to}, the take-off velocity and vertical displacement of COM prior to take-off (COM height at t_{to}) were calculated by integrating the vertical force obtained from the force-plate divided by the body weight. The integration error is assumed to be negligible since the integration interval was short. Then, the vertical jump height was calculated (Moir, 2008).

3.3 Data Analysis

Knowing accuracy as the degree of closeness of a measured quantity to the quantity's actual and precision as the closeness of repeated measurements of the same quantity (Taylor et al., 1983), mean error was considered as a parameter defining the accuracy of measurement and the standard deviation of the mean error was considered as a parameter defining the precision of measurement. To assess the accuracy and precision of the sacrum-mounted IMU sacrum in detecting temporal parameters, the flight duration (t_{to} to t_{td}) and countermovement jump duration (t_{in} to t_{la}) were obtained from both IMU and force-plate. The mean error for each duration was calculated as the difference between the IMU and force-plate measurements. To assess the accuracy of the IMU in estimating jump height, the difference with those obtained by the force-plate and motion-capture cameras was calculated. The errors for temporal parameters and jump height were averaged among the two trials for each condition and for each participant. Then, the median and first and third quartiles of these averages among participants were calculated. Moreover, Pearson's correlation coefficient was used to investigate the correlation between jump height obtained by the IMU, motion-capture cameras, and force-plate. The data analysis was performed using MATLAB (R2018b, MathWorks, USA).

3.4 Results

The mean errors of IMU (standard deviation) in measuring the flight duration and countermovement jump duration were 0.06 (0.17) sec (mean among participants) and -0.03 (0.20) sec, respectively, for the countermovement jump with arm swing and 0.16 (0.22) sec and -0.7 (0.24) sec, respectively, for the countermovement jump without arm swing (**Figure 11**).

The mean error (standard deviation) of the jump height obtained using IMU compared to that obtained using the force-plate were 1.8 (2.0) cm and -0.4 (2.4) cm with no significant difference (p= 0.77 and 0.70 respectively), during the countermovement jump with arm swing and without arm swing, respectively (**Figure 12**).

In comparing the jump height obtained using IMU with that obtained using the motion-capture system, the mean errors were 0.2 (2.1) cm and 1.1 (3.0) cm with no significant difference (p = 0.61 and 0.68, respectively) during the countermovement jump with arm swing and without arm swing, respectively (**Figure 12**).

In comparing the jump height obtained using the two reference systems, i.e., force-plate and motion-capture system, the mean errors were 1.5 (1.8) cm and 0.7 (3.2) cm, during the countermovement jump with arm swing and without arm swing, respectively (**Figure 12**).

Jump heights estimated from IMU and force-plate were correlated for jumps with arm swing (r = 0.81, SEE = 3.6 cm) and without arm swing (r = 0.80, SEE = 3.0 cm). Furthermore, jump heights estimated from IMU were correlated with estimates from the motion-capture system for jumps with arm swing (r = 0.91, SEE = 2.2 cm) and without arm swing (r = 0.78, SEE 2.9 cm) (**Table 1**, **Figure 13**).

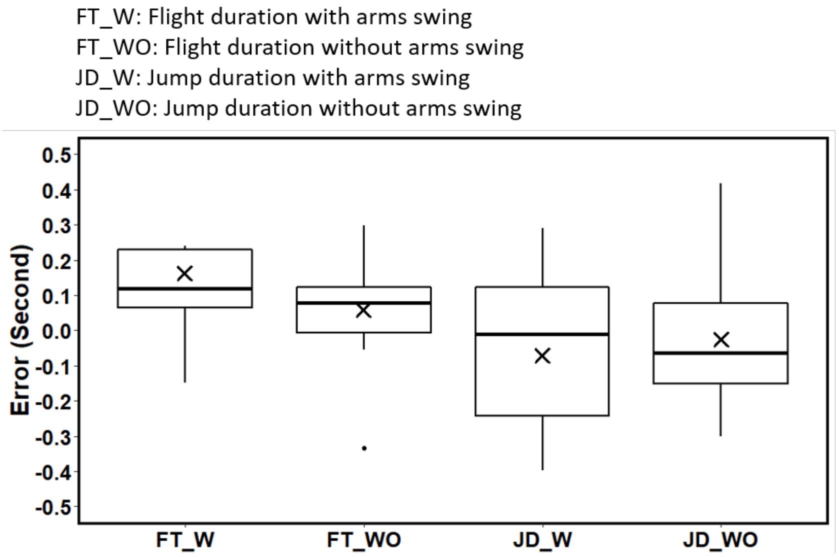

Figure 11 Error of the flight duration (sec) and CMJ duration detection using a sacrum-mounted IMU presented as boxplot among all participants. 'X' indicates the mean error.

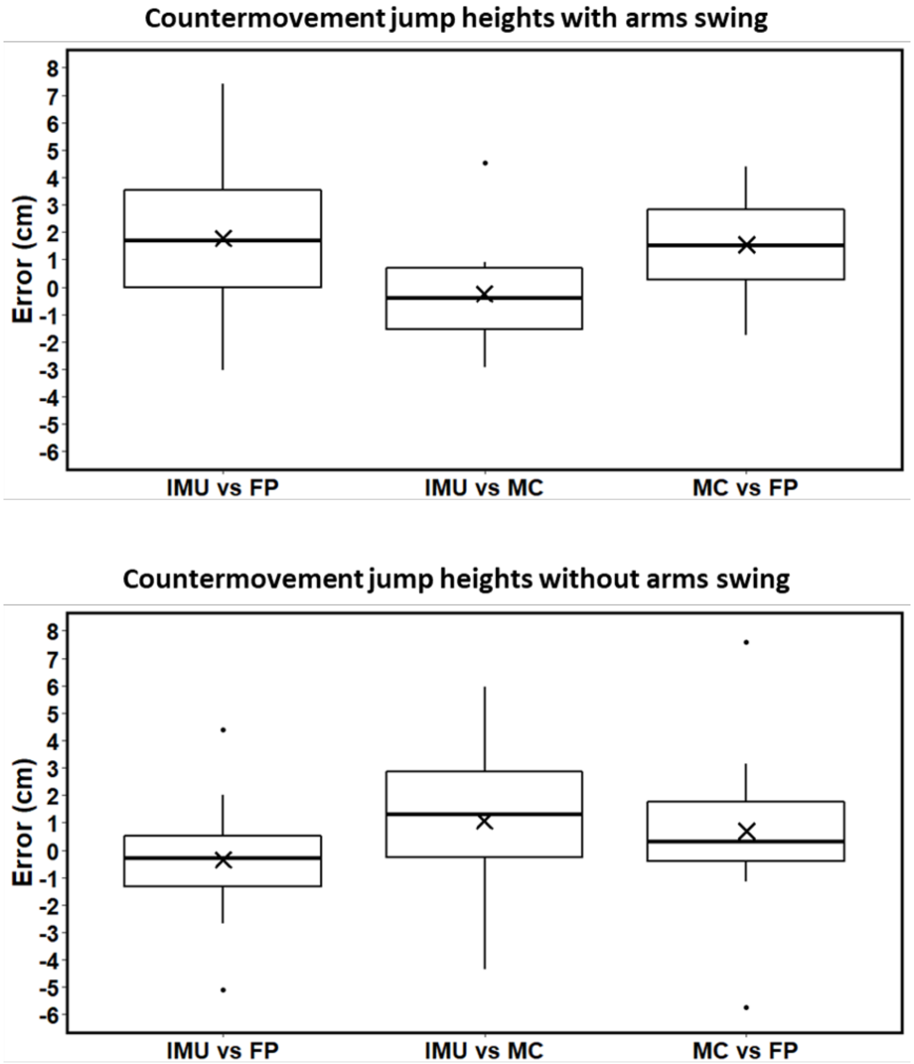

Figure 12 Error of the jump heights obtained by the sacrum-mounted IMU, motion-capture system (MC), and force-plate (FP) with respect t each other. The errors are presented as boxplots among all participants. 'X' indicates the mean error.

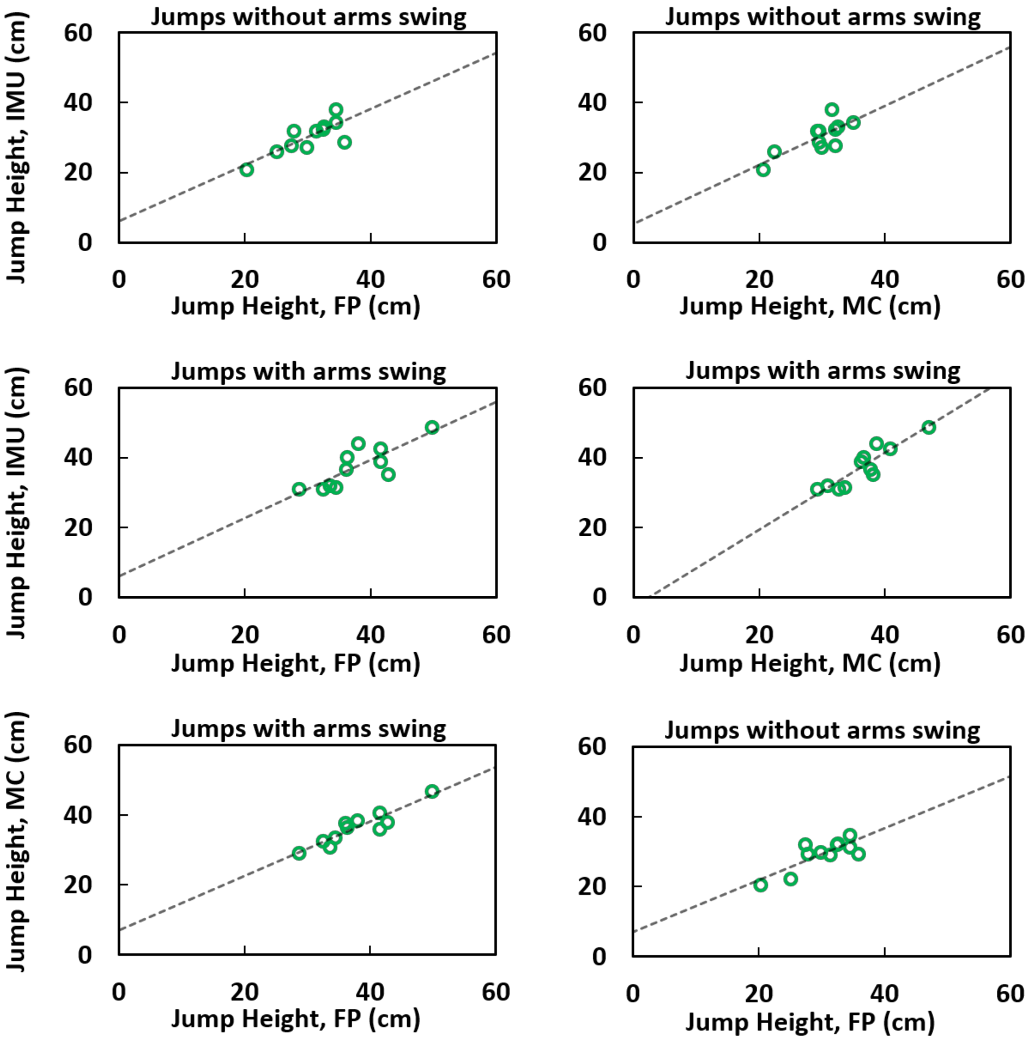

Figure 13 Comparison of jump height estimated using force-plate (FP), IMU, and motion-capture system (MC) presented in the form of scatterplots.

Table 1: Linear regression analysis presented in the Standard Error of Estimation (SEE) and Pearson's correlation coefficient (r) between jump heights estimated using force-plate (FP), IMU, and motion-capture system (MC). Results are expressed as SEE (cm) [r].

	Without Arms Swing			**With Arms Swing**		
	FP	**IMU**	**MC**	**FP**	**IMU**	**MC**
FP	-	3.0 [0.80]	2.9 [0.80]	-	3.6 [0.81]	2.4 [0.92]
IMU	3.0 [0.80]	-	3.1 [0.78]	3.7 [0.81]	-	2.7 [0.91]
MC	2.7 [0.80]	2.9 [0.78]	-	2.0 [0.92]	2.2 [0.91]	-

3.5 Discussion

This study presented a method to estimate vertical jump height (vertical displacement of the COM from the beginning of the countermovement jump to the peak of jump) using a sacrum-mounted IMU during countermovement jump with and without arms swing. In contrast to previous studies (Innocenti et al., 2006; Palma et al., 2008; Picerno et al., 2011; Quagliarella et al., 2010; Rantalainen et al., 2018c), this method was not limited to the COM displacement during the flight phase. Furthermore, the orientation of the pelvis was measured and considered in the calculation of acceleration and estimation of jump height for both countermovement jumps with and without arm swing.

In this study, i) the accuracy of our proposed method in estimation of jump height using an IMU, and ii) the detection of initiation, take-off, touch-down, and landing time instants in the form of flight and countermovement jump duration using an IMU, were comprehensively investigated and validated against those obtained by force-plate and motion-capture system. The choice of two criteria aimed to characterize the error associated with the jump height calculation based on flight-time detection and COM trajectory estimation, which are both applicable to the IMU recordings. To this end, we also investigated the effect of arms swing on the accuracy of estimated jump height using an IMU.

3.5.1 Estimation of time instants

Our proposed method for estimating the t_{in}, t_{to}, t_{td}, and t_{la} time instants using a sacrum-mounted IMU showed high accuracy. The mean error of flight duration (t_{to} to t_{td}) and countermovement jump duration (t_{in} to t_{la}) were 0.06 (0.17) sec, and -0.03 (0.20) sec, respectively, for the countermovement jump with arms swing, and 0.16 (0.22) sec, and -0.07 (0.24) sec, respectively, for the countermovement jump without arms swing (**Figure 11**). Since the sampling frequency of the IMU was 100 Hz, these errors are comparable to one sampling interval (0.10 sec), and thus were minimal. As a result, a sacrum-mounted IMU was able to detect temporal events and define the start and stop time of integration for jump height estimation.

3.5.2 Estimation of Jump height

The mean error (standard deviation) of the jump heights (**Figure 12**) without arms swing obtained by a sacrum-mounted IMU were -0.4 (2.4) cm and 1.1 (3.0) cm compared to the heights obtained by the force-plate and motion-capture cameras, respectively. Additionally, high correlation (r = 0.82 and r = 0.71) and no significant difference (p = 0.77 and p = 0.61) were observed between the jump height estimated using IMU and those calculated using force-plate and motion-capture systems, respectively (**Table 1**,**Figure 13**). Also, no significant difference (p = 0.96) and a mean error (standard deviation) of 0.7 (0.32) cm were found between the jump height obtained by force-plate and motion-capture systems (**Figure 12**). The SEE of jump heights between the IMU and the reference methods (force-plate and motion-capture systems) were 3.0 cm and 2.9 cm, respectively, which are similar to the SEE of 2.9 cm between force-plate and motion-capture system.

The contribution of arms to body mass is about 10% (Dumas et al., 2007). The arms swing affects the body COM position. Since the sacrum-mounted IMU was not able to identify the change in the body COM due to arms rise, it was expected to observe a decrease in accuracy of jump height estimation using the IMU during the CMJ when the arms swing. The contribution of arms swing in the COM affected the mean error (standard deviation) and changed it from -0.4 (2.4) cm and 1.1 (3.0) cm to 1.8 (2.0) cm and 0.2 (2.1) cm compared to the force-plate and motion-capture system, respectively (**Figure 12**). The jump heights estimated by the IMU was still highly correlated to force-plate and motion-capture system methods (r = 0.81 and r = 0.91, respectively) with no significant difference (p = 0.70 and p = 0.68, respectively (**Table 1**,**Figure 13**). Arms swing also affected the mean error (standard deviation) between the reference methods as it was increased from 0.7 (3.2) cm to 1.5 (1.8) cm due to the contribution of arms swing. In addition, Pearson's correlation coefficient was increased from 0.80 to 0.92 between the reference systems. Although the mean errors increased with the addition of arms swing, the accuracy of the IMU for jump height estimation was still in the same range for the CMJ with and without arms swing.

In summary, we observed that assuming the body COM is on the sacrum during the CMJ with and without arms swing would be able to provide an estimation of the jump height, and our employed zero-velocity and zero-vertical displacements corrections limited the accumulated errors. Notably, the SEE values tended to be large compared to the mean error of jump heights obtained by a sacrum-mounted IMU compared to force-plate and motion-capture cameras. It indicates that there were random errors rather than systematic errors in the jump heights estimated using the sacrum-mounted IMU, compared to those measured by the force-plate and motion-capture cameras. These errors were partly caused by inaccuracies in assuming the sacrum as the COM location since the motion of lower and upper limbs could not be tracked by the sacrum-mounted IMU. Also, the error in the jump heights measured by the IMU and cameras compared to those measured by the force-plate could be caused by the difference between their sampling frequencies. Previous studies revealed the outcome accuracy of the integration of force-plate data was affected by its sampling frequency. Similarly, the accuracy of estimated jump height using IMU at 100 Hz, compared to that measured by force-plate at 1000 Hz, may increase if the IMU's sampling frequency increases. Finally, the unwanted movement of the sacrum-mounted IMU caused by soft tissue artifact could negatively impact the accuracy of its estimated jump height.

3.5.3 Limitations

The first limitation of this study was using half body marker set and assumption of symmetry motion during countermovement jump for the motion-capture system. Also, we observed that assuming that the body COM is on the sacrum during the CMJ with and without arms swing would be reasonable. However, this assumption might not be valid for more complex motions, due to the upper and lower limbs' motion relative to the trunk and pelvis. Placing other IMU's on the upper or lower limbs should be considered for COM location estimation of such movements.

3.6 Conclusion

This study showed that our proposed sacrum-mounted IMU has similar errors to motion-capture system in estimating the CMJ heights with and without arms swing, although it may not be used as a substitute for force-plate. Since errors in IMU measurements compared to force-plate were similar to the ones observed in motion-capture system, further studies might be conveyed to reduce the error of IMU compared to the force-plate. In contrary to the motion-capture cameras and force-plate, the IMU is inexpensive and easy-to-use, and can be used outside the lab environment with little training. Although the arms swing slightly affected the accuracy of the jump height estimation using a sacrum-mounted IMU, this accuracy was still comparable to the difference between the measurement of the force-plate and cameras. Despite the high correlation between measured jump height obtained by IMU, fore-plate and motion-capture cameras, the standard error of estimation for the jump height obtained by IMU compare to force-plate and motion capture is larger than the mean error, indicating a lower precision of the sacrum-mounted IMU compared to its accuracy. Future studies should investigate the practical suitability of the sacrum-mounted IMU for performance assessment of athletes or those with reduced mobility.

4 Application of a Sacrum-mounted IMU in Detection of Neuromuscular Fatigue: Technical Validation Against a Force-plate

4.1 Introduction

Previous studies have shown a strong relationship between spatiotemporal parameters of the CMJ (e.g., jump height and flight time) and neuromuscular function and athletic performance (Hudgins et al., 2013). CMJ parameters such as peak and mean power and force, flight time, time to peak force, the velocity at peak power, total impulse, and flight time (Boullosa et al., 2011; Cormie et al., 2010, 2009; McLellan et al., 2011) have been proposed and investigated to identify and monitor neuromuscular fatigue. One of the measures introduced in the literature for identification of neuromuscular fatigue is the ratio of the flight-time to the contraction time (FT:CT) (Cormack et al., 2013, 2008; Mooney et al., 2013). A substantial decrease in the FT:CT ratio is reported for the fatigued group compared to the non-fatigued group of athletes. A force-plate is usually used for the assessment of the spatiotemporal parameters of CMJ. Yet, it is expensive and its application is limited to a dedicated lab environment. In Chapter 3, we showed how a sacrum-mounted IMU could estimate the body COM motion during CMJ as well as the CMJ temporal parameters. The purpose of this study is to evaluate the accuracy and precision of a sacrum-mounted IMU in the measurement of CMJ parameters with the potential to characterize neuromuscular fatigue. For this purpose, the FT:CT ratios obtained by a sacrum-mounted IMU was experimentally compared to those obtained by force-plate as a reference system.

4.2 Materials and methods

4.2.1 Measurement systems

For this study, two measurement systems were used. An IMU (MTws, XSENS Technologies, NL) was attached to the participant's sacrum via double-sided medical tape and was secured in a way that limited the soft tissue artifacts. The sacrum's 3D acceleration and 3D angular velocity were recorded using the IMU at 100 Hz. Also, a force plate (OR6-7, AMTI, Watertown, MA, USA) was used to record the ground reaction forces at 1000 Hz, synchronously with the IMU, while the participant performed CMJ. The force-plate was used as a reference system to measure the accuracy of the detection of fatigue-related temporal parameters using the IMU during CMJ.

4.2.2 Experimental procedure

This study involved eleven participants (all male, age: 27 ± 2, body mass: 74 ± 7 kg, body height: 179 ± 5 cm). Ethical approval was obtained by the Research Ethics Board Committee of the University of Alberta (Pro00085074). The participants were briefed on the experiment, and written informed consent forms were collected before the experiment. First, they were asked to perform two barefoot CMJs with, and two CMJs without arms swing on the force-plate while the IMU was placed on their sacrum. Then, they were asked to jump continuously until they feel muscle fatigue that was perceived to considerably impact their jumping performance. Finally, they performed two CJMs, one with and one without arms swing after the fatiguing jumps.

4.2.3 Estimation of the fatigue-induced parameter during countermovement jump

An entire CMJ duration can be broken down into the following phases: quiet standing phase, countermovement phase (including unweighing, braking, and propulsion), flight phase, and landing phase (Casartelli et al., 2010; McMahon et al., 2018; Setuain et al., 2015; Vanrenterghem et al., 2004, 2001). These four phases are separated by the initiation time (t_{in}), take-off time (t_{to}), touch-down time (t_{td}), and landing time (t_{la}). In Chapter 3, we tested different algorithms to detect these time instants based on the acceleration and angular velocity measured using the IMU and introduced the most accurate algorithm for this purpose. Here we calculated the FT:CT ratio based on these the time instants. To validate the IMU's accuracy for FT:CT ratio estimation, we compared the FT:CT ratios calculated by the IMU against those obtained based on the vertical ground reaction force measured by the force-plate. We obtained t_{in}, t_{to}, t_{td}, and t_{la} using force-plate and IMU and according to Chapter 3. Then, the contraction time was calculated by deducting t_{in} from $t_{to,}$ and the flight time was calculated by deducting t_{to} from t_{td}. FT:CT ratio was calculated, dividing the flight time to contraction time for each CMJ.

4.3 Data Analysis

Similar to Chapter 3, mean error was considered as a parameter defining the accuracy of measurement and the standard deviation of the mean error was considered as a parameter defining the precision of measurement. FT:CT ratios of four pre-exercise CMJs and two post-exercise CMJs were calculated for each participant. The mean error for each FT:CT ratio was calculated as the difference between the IMU and force-plate measurements. The mean errors were averaged among the three CMJs with and without arms swing for each participant. Then, the median and first and third quartiles of these averages among participants were calculated. Furthermore, Pearson's correlation coefficient was used to investigate the correlation between the FT:CT ratios obtained from the sacrum-mounted IMU and those from force-plate. Finally, the relative change in FT:CT ratio from the pre-exercise to post-exercise CMJs obtained by the sacrum-mounted IMU were compared to those obtained by the force-plate. The data analysis was performed using MATLAB (R2018b, MathWorks, USA).

4.4 Results and Discussion

The mean errors (standard deviation) of FT:CT ratio estimated using sacrum-mounted IMU against the force-plate were 0.069 (0.085) and 0.132 (0.068) with no significant difference ($p = 0.03$ and $p = 0.06$) for CMJs with and without arms swing, respectively (**Figure 14.a**). The relative mean errors (standard deviation) of FT:CT ratio estimated using sacrum-mounted IMU against the force-plate were 11.7% (13.3%), and 23.2% (11.7%) for CMJs with and without arms swing, respectively (**Figure 14.b**). FT:CT ratios estimated from IMU and force-plate were correlated for jumps with arms swing ($r = 0.68$, SEE = 0.13) and without arms swing ($r = 0.79$, SEE = 0.12) (**Figure 15**). The relative mean error (standard deviation) of change in FT:CT estimated using the sacrum-mounted IMU against to force-plate were 7.6% (16.8%) and 9.5% (25.3%) normalized to pre-exercise ratios measured using the same device for the CMJs with and without arms swing, respectively (**Figure 16**). The relative changes in FT:CT ratios estimated from IMU and force-plate were correlated for jumps with arms swing ($r = 0.85$, SEE = 0.22) and without arms swing ($r = 0.73$, SEE = 0.26) (**Figure 17**)

As such, relatively low mean errors and relatively high correlation coefficients were observed for FT:CT ratios obtained by the IMU against those measured by the force-plate in both CMJs with and without arms swing conditions. It was observed that the sacrum-mounted IMU overestimated the FT:CT ratio showing a significant difference with zero for both CMJs with ($p < 0.01$) and without arms swing ($p < 0.01$); yet, the mean errors were small. The overestimation of

FT:CT ratio could be caused by overestimation in flight-time observed in Chapter 3. Also, smaller mean error and standard deviation in FT:CT ratios and higher correlation between the FT:CT ratios obtained by the IMU and those obtained from force-plate were observed in the CMJ with arms swing compared to those without arms swing. These observations revealed that the sacrum-mounted IMU was more accurate and precise in estimating FT:CT ratio CMJ with arms swing compared to CMJ without arms swing.

The relative change in the post-exercise FT:CT ratio compared to the pre-exercise FT:CT ratio did not show any significant difference with zero when measured by both IMU and force-plate. Also, the relative change in the FT:CT ratio measured by both devices were correlated with each other. Both force-plate and sacrum-mounted IMU showed a similar trend in the detection of neuromuscular fatigue based on the CMJ test performance.

The importance of FT:CT ratio is in defining a baseline to assess each individual performance and distinguish fatigued from the non-fatigued situation (Cormack et al., 2013, 2008; Gathercole et al., 2015). We quantified this potential using the relative change of FT:CT from the pre-exercise CMJ to the post-exercise one. The SEE values of the FT:CT change tended to be larger compared to the observed mean error of the FT:CT change. This indicates that the estimated FT:CT change was affected mostly by random errors rather than systematic errors. Similar to our observations in Chapter 3, the random errors could be caused by the difference between the sampling frequency of the IMU and force-plate. Finally, the movement of the sacrum-mounted IMU caused by soft tissue artifact could negatively impact the precision of its measured FT:CT ratio.

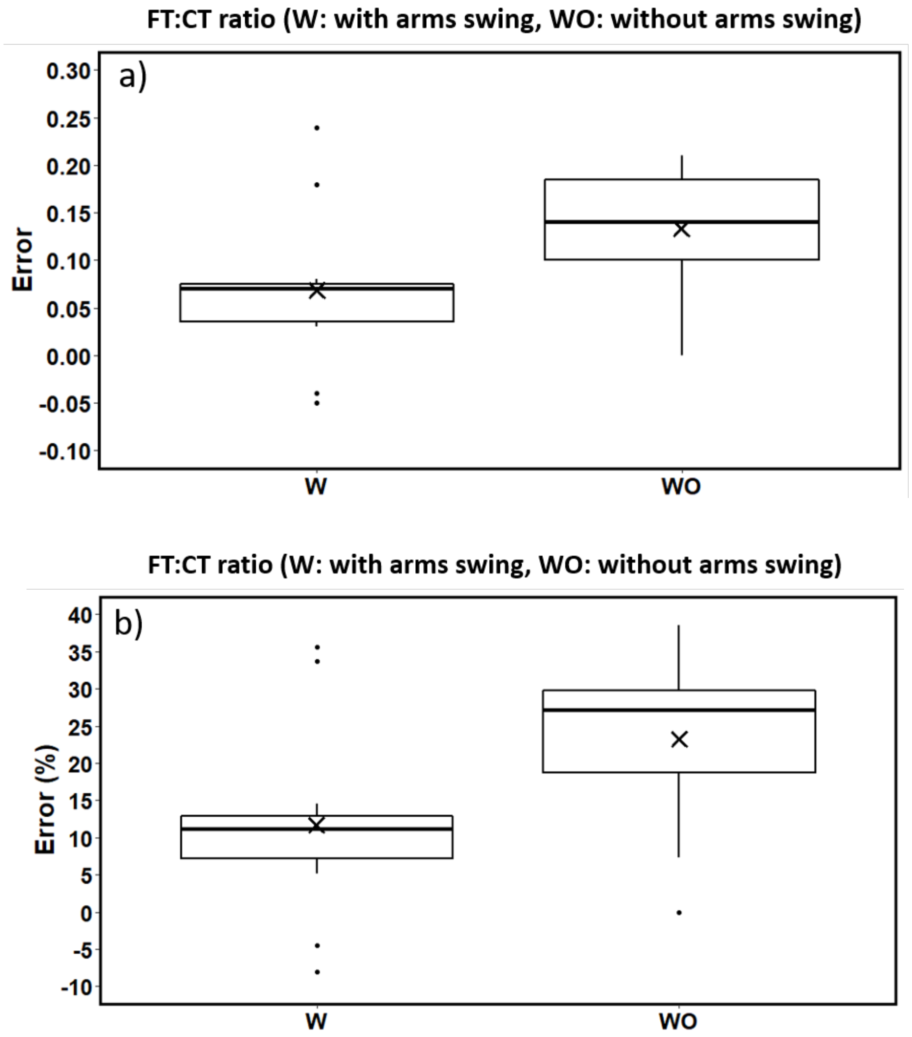

Figure 14 Error of the FT:CT ratio using a sacrum-mounted IMU for CMJ with arms swing and without arms swing compared to force-plate presented as boxplot among all participants. Plots (a) and (b) show the absolute FT:CT error and the relative error (%) normalized to the force-plate measurement, respectively. 'X' indicates the mean error.

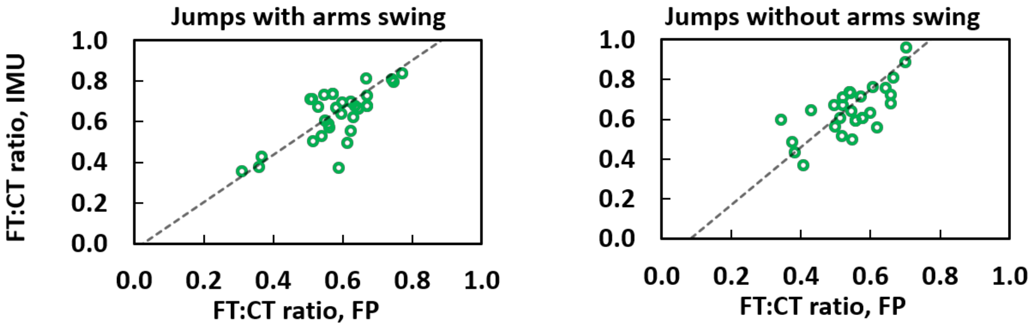

Figure 15 Comparison of FT:CT ratios estimated using IMU and force-plate (FP) for CMJ with and without arms swing presented in the form of scatterplots.

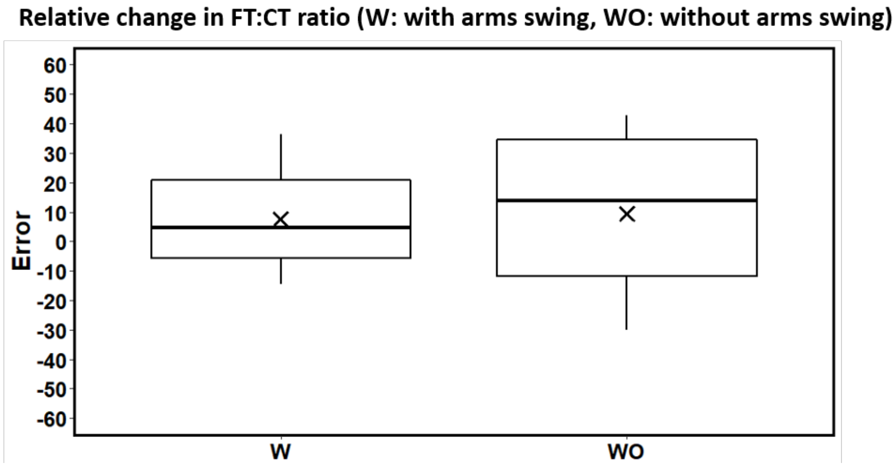

Figure 16 Error of the relative change in FT:CT ratio normalized to pre-exercise ratios (%) from pre-exercise CMJ to post-exercise CMJ using an IMU for CMJ with arms swing (left) and without arms swing (right) compared to force-plate presented as boxplot among all participants. 'X' indicates the mean error.

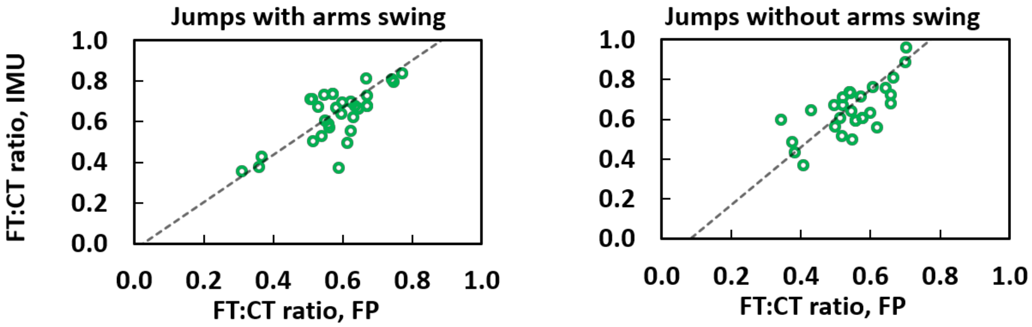

Figure 17 Comparison of relative change in FT:CT ratios from pre-exercise CMJ to post-exercise CMJ estimated using IMU and force-plate (FP) for CMJ with and without arms swing presented in the form of scatterplots.

4.5 Conclusion

This study revealed that the sacrum-mounted IMU was able to provide an estimation of the FT:CT ratio for CMJ with and without arm swing. The FT:CT change between the pre-exercise and post-exercise has the potential to detect neuromuscular fatigue. Although we observed no major FT:CT change in most participants after exercise, both force-plate and IMU showed a similar trend in the measurement of FT:CT change for each participant. Therefore, the IMU has the potential to be an inexpensive and easy-to-use alternative to the force-plate for measurement of post-exercise fatigue based on the CMJ test out of the lab environment. Yet, future studies should investigate the practical suitability of a sacrum-mounted IMU in identifying neuromuscular fatigue with a larger population size and inclusive fatiguing experimental procedure.

5 Conclusion and Future Perspectives

5.1 General Results and Main Contributions

The main contributions of this thesis project were to 1) develop a wearable technology based on a sacrum-mounted IMU for in-field assessment of CMJ-related parameters and 2) experimentally validate its accuracy and precision against force-plate and motion-capture system. CMJ-related spatiotemporal parameters studied in this thesis project were time instants (initiation, take-off, touch-down, landing), time durations (flight time, contraction time, and flight time to contraction time ratio), and jump height. To this end, we developed algorithms which were able to provide estimation of these spatiotemporal parameters of CMJ with and without arms swing. The findings of this thesis are summarized in the following sections.

5.1.1 Assessment of CMJ with and without Arms Swing Using a Single Sacrum-mounted IMU

It was observed that sacrum-mounted IMU is able to provide meaningful estimation for duration of temporal phases and height of CMJ with and without arms swing, compared to the motion-capture system and force-plate. In contrary to the motion-capture cameras and force-plate, the IMU is inexpensive and easy-to-use, and can be used outside the lab environment with little training. The arms swing slightly affected the accuracy of the jump height estimation using a sacrum-mounted IMU. Flight duration, jump duration, and jump height obtained by IMU compared to force-plate showed that the IMU could not be used as a substitute for force-plate. Yet, errors in IMU measurements compared to force-plate were similar to the ones observed in motion-capture system. As a result, further studies might be conveyed to reduce the error of IMU compared to the force-plate.

5.1.2 Technical Validation of Neuromuscular Fatigue-related Parameters

Our proposed algorithms enabled the sacrum-mounted IMU to estimate the FT:CT ratio, as a temporal parameter identifying neuromuscular fatigue, during CMJ with and without arms swing. Although the sacrum-mounted IMU detected similar trends in the post-exercise changes in the FT:CT ratio, compared to force-plate measurements (for CMJ with and without arms swing), errors were observed in the sacrum-mounted IMU measurements. Further studies are needed to explore the potential of the sacrum-mounted IMU to detect neuromuscular fatigue out of the lab environment.

5.2 Future Perspectives

5.2.1 Improving the Accuracy and Precision of Temporal Phases and CMJ Height Estimation

Accuracy of detecting time instants plays a vital role in the accuracy of jump height estimation. The sampling frequency of the sacrum-mounted IMU and noises caused by soft tissue artifact were two major sources of error in detecting the time instants. In this study, the sacrum-mounted IMU had a sampling frequency of 100 Hz that was lower than that of the force-plate (1000 Hz). It would be beneficial to investigate the effect of IMU's sampling frequency on the accuracy and precision of estimation of the temporal phases and CMJ height. Notably, the higher sampling frequency may also decrease the accumulated error of numerical integration used for CMJ height estimation. Also, it is recommended to investigate the effect of different digital filters in reducing the noise caused by the soft tissue artifact, which can affect the accuracy of detecting the time instants and the CMJ height.

5.2.2 Practical Validation of Neuromuscular Fatigue Related Parameters

The CMJ is proposed as a functional test to assess the strength and neuromuscular performance of athletes. In this study, the accuracy of the sacrum-mounted IMU in estimating FT:CT ratio and FT:CT change was investigated against force-plate. Same trend in FT:CT ratio was observed by IMU and force-plate during a session containing pre-exercise and post-exercise CMJs were no neuromuscular fatigue was reported. Yet, it is not clear whether the accuracy is enough for monitoring and identifying neuromuscular fatigue after more demanding or longer exercises. For future studies, it is recommended to investigate the FT:CT ratios before and after intensive long-term activities in which the individuals experience significant neuromuscular fatigue. It this way, the pre and post-exercise FT:CT ratios obtained by a sacrum-mounted IMU can be compared together so that the potential of the proposed instrumented CMJ test for neuromuscular fatigue detection can be further investigated.

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