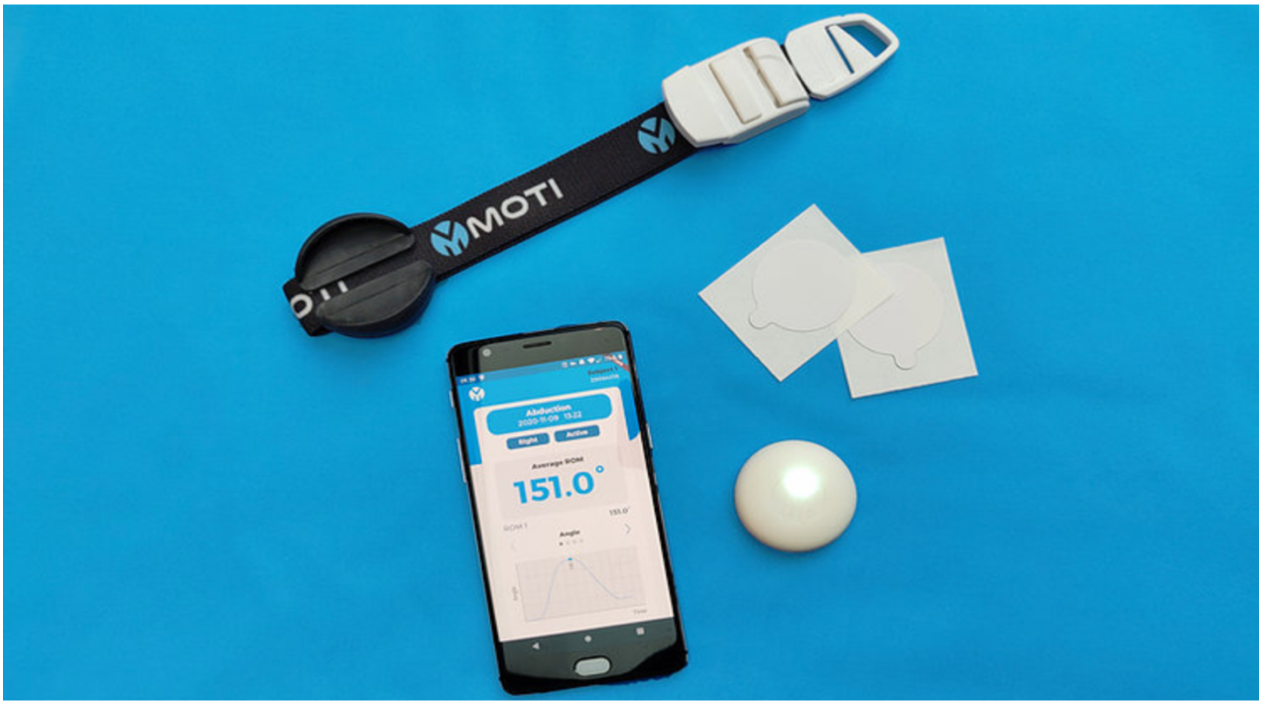
Validation of MOTI sensor in relation to Return to Sport criteria for dynamic stability in ACL injuries



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Abstract

Introduction: The incidence of ACL injuries in younger adults is approximately 1-4%, and there is a high risk of a re-rupture. 35% of those who have an ACL injury do not return to sport two years after the injury, and 12-23% of athletes end their careers because of the injury. The current rehabilitation after an ACL injury includes different stages with different criteria. However, these criteria, especially in the RTS stage, have limited effects. It is recommended implementation of qualitative measures of neuromuscular control to potentially improve the effects of rehabilitation on the risk of re-rupture and improve the RTS rate. The purpose of this project is therefore to test the validity and reliability of MOTI by comparing measures of dynamic stability (TTS) on single-leg landings objectively up against a force platform.

Method: This project included a cross-sectional design and consisted of one experimental session that lasted 30 minutes. There were recruited 30 healthy participants who performed three trials of three different single-leg landing tasks onto a force platform while MOTI was placed on the lower back. The force platform is considered the gold standard. TTS values were measured for each participant in all movements. Test-retest reliability was analyzed with ICC, SEM and MDC for each task, and validity was analyzed through an ICC and Bland-Altman plot to show limit of agreement between MOTI and the force platform.

Results: Reliability of MOTI showed poor agreement between trials in all movements with ICC values ranging between 0.269 – 0.491. Reliability of the gold standard showed similar poor results, except in movement SL, where reliability was moderate. Validity of MOTI was poor with ICC values ranging from 0.191 – 0.413, LoA presented a large variety between measurement (FL: Loa = 0.415; SL: LoA = 0.368; DL: LoA = 0.387) and a slight, but non-significant underestimation of MOTI in movement FL and DL, and a significant underestimation in SL (FL: Mean diff = 0.064; SL: Mean diff = 0.092; DL: Mean diff = 0.0.067).

Conclusion: MOTI is not a reliable or valid tool for measuring dynamic stability through TTS in single-leg landing tasks compared to a gold standard (force platform).

Preface

This master thesis has been produced during the spring of 2021 by project group gr10607 consisting of one student studying in the 4th semester of the master's program in Musculoskeletal Physiotherapy at Aalborg University. The group's only member has a background as a physiotherapist with a bachelor's degree and clinical experience.

The author would like to thank Thorvaldur Skuli Palsson for supervision and guidance throughout the entire process. And a further thanks to Rogerio Hirata for the assistance with the processing and extraction of data. Lastly, a huge thanks to MOTI developers, who were helpful, cooperative, and available during the months of cooperation and the contribution of a facility where the experiment could take place.

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1. Introduction

The prevention and rehabilitation of physical activity and sport injuries are essential for active individuals in their daily lives (Bueno et al., 2018). This is because injuries are often associated with and can result in decreased function and participation in activities (Bueno et al., 2018). Injuries to, e.g., the Anterior Cruciate Ligament (ACL) are a common and devastating injury linked to short-term disability and long-term impairment (Paterno et al., 2010a). In general, there seems to be a higher incidence of ACL injuries in persons who are 15-45 years. There are about 2.2 million people in Denmark in this age span range, where the majority (60 percent) are physically active. Furthermore, many of these regularly engage in activities with a high incidence of ACL injuries ((0.8-2.4 percent of males and 2.0-3.2 percent of females) (Moses et al., 2012; Prodromos et al., 2007). In addition, it is reported that in professional athletes, the incidence can be higher (up to 15 percent) (Moses et al., 2012). When the injury has occurred, approximately 35 percent of those who undergo an ACL reconstruction operation (ACL-R) have not returned to the desired level of sport after two years, and it is reported that in elite athletes, 65 – 79 percent return to their level of competition. However, there are reports that 12-23 percent do reduce their level or end their careers due to the injury (Davies, William T. et al., 2020). In addition to the rate of return to sport, can the rate of reinjury (e.g., second ACL rupture) be as high as 35 percent in younger athletes (Ardern et al., 2011; Ardern et al., 2014; van Melick, Nicky et al., 2016; Webster, Kate & Hewett, 2019). Those who return to the same level of sport also have an increased risk of reinjury or further damage to the ACL (Webster & Hewett, 2019). Approximately half of the patients report that the ACL injury is the main reason for this decrease in physical activity. However, psychological elements like fear of reinjury, fear of pain, kinesiophobia affect the level of activity to which the patient chooses to return to and quality of life (van Melick et al., 2016)

1.1. Treatment options

In a knee injury such as an ACL rupture, there are different treatment options. According to recent clinical guidelines, the main treatment options for an ACL rupture are divided into three, 1) Rehabilitation as primary treatment, followed by an ACL-R if patient presents themselves with functional stability, 2) ACL-R as a first-line treatment followed by postoperative treatment, 3) ACL-R after an preoperative rehabilitation and a postoperative rehabilitation (Filbay & Grindem, 2019). However, there are minimal differences in functional, radiographic, and patient-reported outcomes between those who managed solely through rehabilitation versus those who undergo an ACL-R. This slight difference makes the foundation for the management of patients require individualization and shared decision to ensure a higher level of success.

1.2. Evaluation and return to sport

The rehabilitation after an ACL rupture has changed from a time-based rehabilitation to an individualized and criterion-based rehabilitation (Filbay & Grindem, 2019). This controls and ensures the progression and that the functional and biological capacity of the patient has developed accordingly. The rehabilitation is often divided into five stages containing principles of individualization and some criteria for when to progress from one stage to the next. The description of phases is in Table 1 (Filbay & Grindem, 2019; van Melick et al., 2016). It is particularly in phases 3-5 that it can be challenging to determine when to progress towards returning to sport as these have elements that require a subjective evaluation of knee movements and control.

Table 1 Rehabilitation phases after an ACL injury

Rehabilitation phase	Main goal	Description
Phase 1 / Preoperative phase	- Limited effusion - Full AROM and PROM - Symmetry of 90 percent in quadriceps strength	For those who plan to undergo an ACL-R. Special attention to passive ROM of knee extension and quadriceps strength. Presentation of full ROM, no effusion, and ability to perform single-leg landings, then heavy resistance training and plyometric exercises are advised.
Phase 2 / Acute Phase	- No joint effusion - Full AROM and PROM - Ability to perform SLR actively in a controlled fashion	Should start straight after ACL rupture or reconstruction. Implementation of weight-bearing such as walking can only occur when there is no pain, effusion, and other signs of overloading during or shortly after. Cryotherapy can help to manage the pain up to one week after injury/surgery. Recommendation of active exercises. Start with isometric exercises followed with CKC or OKC, depending on the type of tendon graft. Patients can perform CKC exercises two weeks post-operation/injury and OKC 4 weeks post-operation/injury. Start with movement within 90-45^{o,} then in week five 90-30^{o,} and so on to full ROM in week 8. In addition, electrostimulation to activate voluntary contractions in quadriceps during the first weeks.
Phase 3 / Intermediate Phase	- Control of knee extension in weight-bearing positions - 80 percent symmetry of strength in quadriceps - 80 percent hop test symmetry - Acceptable quality of movement.	Neuromuscular training targets the ability to stabilize the knee in dynamic movements—results in better proprioception and motor control. Strength training targets the ability to produce power and strength to engage in a higher activity level like sport and recreational activities. Exercises that implement both bilateral and unilateral exercises contribute to better outcomes.
Phase 4 / Return to Sport Phase (RTS)	- 90 percent symmetry of quadriceps strength, - 90 percent symmetry by hop test with acceptable movement quality - Self-efficacy and confidence in activities - Implementation of challenging tasks.	Evaluation of sport and activity that patients desire to return for the rehabilitation can be tailored and individualized. RTS is controlled through a staged progression from non-contact training to complete training, restricted attendance in competition, and lastly, unrestricted attendance in competition
Phase 5 / Injury Prevention	- Sustain muscle strength - Sustain dynamic knee stability - Load management	After completed rehabilitation and returning to the sport, an injury prevention plan is advised to be performed two times a week.

Note: ACL-R = Anterior Cruciate Ligament Reconstruction; ROM = Range of Motion; AROM = Active Range of Motion; PROM = Passive Range of Motion; SLR = Straight Leg Raise; CKC = Closed Kinetic Chain; OKC = Open Kinetic Chain.; RTS = Return to Sport

1.3. Initiating problem

Based on the description of phases of rehabilitation after an ACL rupture, it is clear that determining when to progress can be challenging in the later stages of rehabilitation and eventually when it is safe to return to sport. This understates the clinical challenge in determining when an athlete is ready to return to play. Based on this clinical issue, it leads to the initial question about:

How is it possible to objectively evaluate movement quality and symmetry in determining when to RTS following a knee injury?

2. Problem analysis

The purpose of this problem analysis is to validate this project's basis and to gather information on how a person's rehabilitation after an ACL injury/surgery can be improved with regard to RTS criteria. This goal is sought to be achieved by knowledge on RTS criteria.

2.1. Return to Sport (RTS)

In this report, RTS is defined as the process of return to participation, accompanied by competitive sport, with the return to the desired level of performance in mind. Often, this takes an average of 7 months from the operation (Roi et al., 2005). However, there is no connection between the time spent after injury/surgery and the functional limitations for persons who are in rehabilitation to RTS (Myer et al., 2012). Therefore, the focus is on bettering the methods that support a more criteria-based rehabilitation process instead of a time-based rehabilitation, as previously recommended (Barber-Westin & Noyes, 2011; Burgi et al., 2019; Rambaud et al., 2018). Standard criteria for RTS reported in the literature are the assessment of isokinetic strength of the quadriceps and hamstrings, single-leg hop tests, and screening of quality of movement in functional tasks (Davies, W. T. et al., 2020). A commonly used test battery in rehabilitation includes a series of single-leg hop tests of distance to test for functional performance and isokinetic strength. The objective assessment compares the injured leg up with the uninjured leg, with a limb symmetry index (LSI). Here, scores above 90 percent indicates a clinical criterion for the clinical decision to "pass" and therefore complete their rehabilitation (Gokeler et al., 2016). However, this quantification of the performance may not be adequate as previous studies indicate that the biomechanics during landing may predict a reinjury of the ACL (Paterno et al., 2010b). With RTS, there are different ways of loading when landing. In this instance, there is no clear relationship between the LSI and the biomechanical loading of joints angles at the hip, knee, and ankle during a single hop for distance (Xergia et al., 2015). In addition to this, compensatory strategies, e.g., smaller peak knee flexion in the injured knee, occur even though the patient succeeds LSI > 90 percent in single-leg hop tests (Welling et al., 2018). This indicates that the development of the movement quality is different, and this development may not be captured by quantitative measures like distance in hop tests.

In addition, this suggests that the current criteria of > 90 percent LSI of hop distance cannot fully evaluate the functional performance of the knee.

Therefore, it has recently been recommended to include aspects of neuromuscular control evaluation as this can further support decision-making for a more successful RTS (Davies et al., 2020). The role and importance of neuromuscular control in ACL rehabilitation are discussed in the following segment.

2.2. Dynamic stability

As the ACL plays an essential role in movements of the knee, an injury to this ligament can cause many problems. The ACL mechanically helps maintain knee stability and contributes to the sensitivity of change in tension, acceleration, movement direction, and proprioception through the presence of mechanoreceptors (Zimny et al., 1986). Therefore, can an ACL injury cause a partial interruption or disruption of the afferent connections and thereby affect motor control. Taken together, an ACL injury significantly impacts proprioception, postural control, strength, movement, and assigning patterns and therefore cause changes in the neuromuscular control of the knee (Decker et al., 2011; Zimny et al., 1986).

When assessing neuromuscular control of the knee, the focus is often on dynamic stability. The definition of dynamic postural stability is "*An individual's ability to maintain balance while transitioning from a dynamic to a static state*" (Head et al., 2019), hence the ability to regain stability after a dynamic movement. Therefore, evaluating dynamic activities such as single-leg landing may be an appropriate way of evaluating neuromuscular control of the knee as it mimics the sport activities and provides an acceptable challenge for neuromuscular control (Head et al., 2019).

2.3. Objective measurement of qualitative performance

The RTS's phase requires complete control over the knee and lower limb compared to the uninjured leg (van Melick, N. et al., 2016). One measure that is regarded as a function measure of dynamic stability is Time to Stabilization (TTS), which is "the time required to minimize resultant ground reaction forces (GRF) following a single-leg landing task" (Heinert et al., 2018). Report of its reliability shows an Interclass Correlation Coefficient (ICC) = 0.65-0.79 (Heinert et al., 2018). Evaluating dynamic stability objectively and accurately can therefore be of great value for clinicians in the process of RTS. However, there are difficulties in controlling and assessing TTS appropriately without extensive laboratory analysis like force platforms, and it is not realistic to possess such expensive and advanced equipment in a standard clinic.

Therefore, could developments of new and innovative wearable inertial sensors for assessing dynamic stability make it possible for clinicians to make objective choices based on qualitative data of movement. One newly devolved wearable inertial sensor is the MOTI sensor. MOTI is a device capable of acting as a digital goniometer and support motion analysis device. This sensor may introduce a way to enable clinicians to measure the quality of movement objectively. However, whether MOTI can measure dynamic stability (TTS) in a valid and reliable manner is currently not known.

2.4. Problem definition

Based on the problem analysis above, evaluating RTS can be challenging and comes in a many layers. First, there is a limited effect of the current RTS criteria on the reinjury rate and the time of RTS. Secondly, the subjective and objective assessment methods to determine the quality of movement are weak. Lastly, even though new sensor technology may support an objective assessment of dynamic stability (TTS) in a clinical setting, the validity and reliability of such methods are unknown.

2.5. Purpose

The purpose of this project was to test the reliability and validity of MOTI by comparing measures of dynamic stability (TTS) on single-leg landings objectively up against a force platform.

3. Methods

The following section presents the methodological choices made in this project concerning the structure of the experiment, recruitment of participants, procedures, protocol, data collection, data processing, and ethical considerations

3.1. Experimental design and participants

This project had a cross-sectional design and consisted of one experimental session that lasted 30 minutes and recruited 30 healthy participants.

The criteria for participation were that participants were over 18 years, pain-free, non-pregnant, and could perform the jumping tasks required in this study.

3.2. Procedures

3.2.1. *Description of data collection with MOTI sensor*

Data collection included the mounting of the MOTI Digital Goniometer with MOTI Mounting Stickers on the lower back (approximately the location of lumbar level five) on each participant. Bluetooth connected the MOTI device to a Huawei P Smart 2019 and recorded data onto the MOTI Research Application.

The preparation of each participant for the placement of the MOTI device was done with a shaving of the MOTI location on the lower back (level of L5). Shaving was done with disposable razor blades and then washed with a single-use alcohol wipe. Then the MOTI device was mounted onto the participant.

3.2.2. *Description of data collecting with force platform*

Data collection included the recordings of GRF on a force platform sampled at 1000Hz Flintec type: BK2-200kg™. Recordings of data were through OpenSignals Software (v2.2.1, PLUX Wireless Biosignals S.A) on a MacBook Air 2018 (Apple Inc, USA). OpenSignals is the software for data acquisition, visualization, and data collection recorded on the force platform. This data was considered to be the gold standard of this particular project.

3.2.3. *Description of protocol*

<u>Instructions to the participant</u>

Prior to data collection, demographic data (height, weight, and dominant leg) were registered.

For all tasks, the participants were instructed to land on one leg in the center of the force platform, regain their stability (stand still) as fast as possible, and hold that position for 10 seconds. The order of legs being tested was not randomized. Instead, landing always landed on the right leg followed by the left leg, irrespective of leg dominance. The participants performed a sequence of tasks that involved landing on one leg after jumping from the front (Forward Landing), side (Side Landing), or from above (Drop Landing). The order of tasks was likewise not randomized with Front Landing (FL) being first, Side

Landing (SL) second, and Drop Landing (DL) last. Participants were not allowed to drive themself with the use of arm swing. All tasks were performed with the participants facing forwards.

All participants were allowed as many practice attempts as needed for familiarization prior to data collection. Following the familiarization period, the participants got a small break. Data were collected until each participant had three successful attempts on each leg for each task (Head et al., 2019).

The recording was manually simultaneously started on the platform and MOTI. After five seconds, the participants got a verbal cue to jump and then land and stand still for 10 seconds, resulting in approximately a 15 seconds recording on both the MOTI device and force platform.

Tasks

Participants performed a sequence of single-leg hopping tasks where they were to land onto the force platform. These tasks consisted of single-leg FL, single-leg SL, and single-leg DL. Each task is presented in Table 2 and illustrated in Figure 1, Figure 2 and Figure 3. A task was deemed successful when the participants i) landed in the center of the platform ii) without the non-test leg touching the ground.

Table 2 Description of tasks: Forward Landing, Side Landing, and Drop Landing

Tasks	Information
Forward landing (FL)	Distance is 40 percent of body height from the start position (marked with a line of tape) to the center of the force plate. Participants were to stand behind the line and then take a jumping step forward from a double leg position onto the platform and land into a single leg position (Head et al., 2019; Heinert et al., 2018).
Side landing (SL)	The distance was 33 percent of their body height from the start position (marked with a line of tape) to the center of the platform. Participants were to stand behind the line of tape with the medial border of the driving leg. Jump sideways from a double leg position onto the platform into a single leg position (Head et al., 2019)
Drop landing (DL)	Participants were placed on top of a 30cm high box, placed immediately adjacent to the force platform. The participants were instructed to stand in a double leg stance and then step off the box and land in a single leg position (Ho et al., 2019; Ithurburn et al., 2019).

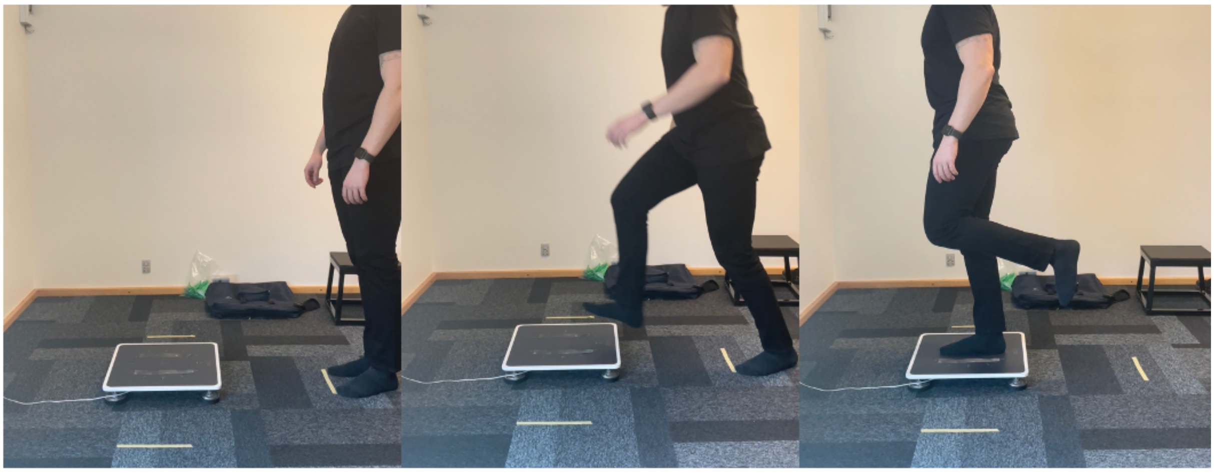

Figure 1 Forward Landing

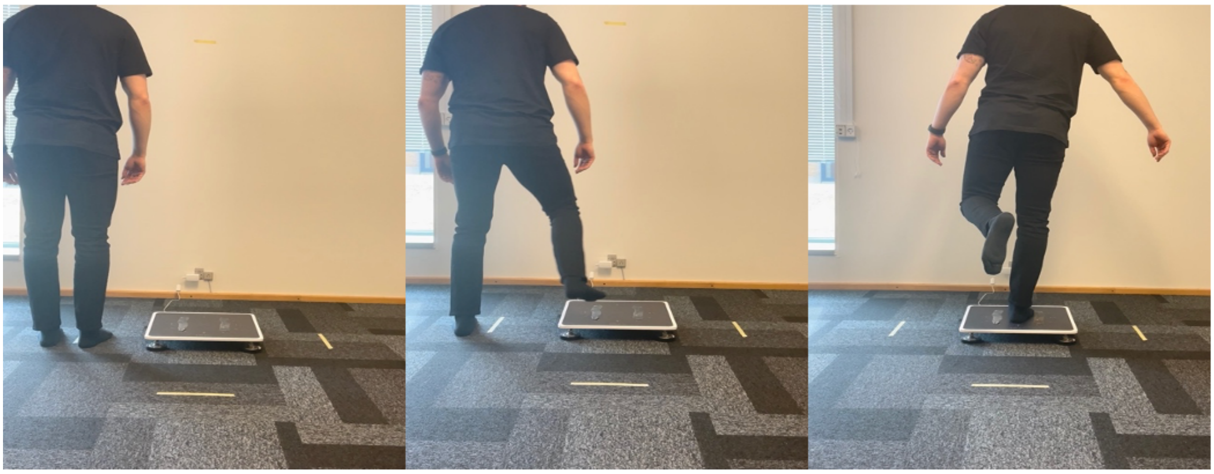

Figure 2 Side Landing

Figure 3 Drop Landing

3.3. Rating of dynamic stability and Data processing

Rating of dynamic stability was done through data from the MOTI sensor and the force platform. The GRF data from the force platform and MOTI data were processed through a custom MATLAB (*The MathWorks, Natick, MA, USA*) script to produce the TTS with each repetition in all three tasks. The method for calculating TTS used a fixed but normalized body weight reference correlating with the body weight from the demographical data for each participant (Huurnink et al., 2019).

3.4. Statistical analysis

As the purpose of the study was to evaluate the performance of MOTI compared with the force platform, the leg dominance was not in focus. Therefore, although data were collected for left and right legs, these were pooled prior to data analysis. Therefore, we had 60 individual legs available for data analysis.

3.4.1. *Reliability*

To determine the test-retest reliability for each of the tasks, TTS data from all three trails from MOTI and the force platform was used to establish both MOTI and force platform's reliability or consistency. After that was the minimal detectable change calculated.

3.4.1.1. Intraclass Correlation Coefficient (ICC)

The test-retest reliability of MOTI was assessed by determining the ICC. Calculation of ICC estimates was done using SPSS statistical package version 23 (SPSS Inc, Chicago, IL) based on single-measurements, absolute-agreement, 2-way mixed-effects model (Koo & Li, 2016).

The ICC values obtained for reliability were interpreted as good if ICC > 0.75, moderate if 0.50 < ICC < 0.75, and poor if ICC < 0.50 (Koo & Li, 2016).

3.4.1.2. Minimal Detectable Change (MDC)

MDC was calculated to indicate the minimum amount of change needed to report a fundamental change in TTS for an individual when measured with MOTI. This was done using the formula: Standard Error of Measurement (SEM) X 1.96 X $\sqrt{2}$, where SEM was derived from the formula: SD × $\sqrt{(1 - ICC)}$, with SD representing pooled Standard Deviation of the measurements (Dontje et al., 2018).

3.4.2. *Validity*

To determine the validity of MOTI, the data from MOTI were compared with the data collected with the force platform. After that, an analysis of agreement was made between the two modalities.

3.4.2.1. Intraclass Correlation Coefficient (ICC)

Validity was first analyzed by assessing means of all trials from MOTI data compared to the means of all trials from the force platform through ICC(3,k). Calculations of ICC were made through mean-measurements ($k = 2$), absolute agreement, and 2-way mixed-effect model.

The ICC values obtained for reliability were interpreted as good if ICC > 0.75, moderate if 0.50 < ICC < 0.75, and as poor if ICC < 0.50 (Koo & Li, 2016).

3.4.2.2. Limit of Agreement (LoA)

A mixed-method ANOVA was performed to look for any systematic differences between the mean TTS of the two measurement methods on each of the tasks. To account for the multiple comparisons, the data were Bonferroni corrected. With three individual tasks, this results in the calculation of: P= 0.05/3 → p = 0.0167. Therefore, a significance level was set as > 0.0167

Limits of agreements (LoA) report if there is an agreement in 95 percent of measures between measures from MOTI and the force platform on each of the tasks. Bland Altman plots were generated to express LoA. This graphical method shows the mean differences between force platform and MOTI against the mean of both measurement methods. A perfect agreement between the two devices would be a demonstration by a mean difference of zero as well as a narrow LoA. Deviations from zero would indicate an over or under-estimation of one of the devices compared to the other.

3.5. Ethical considerations

The project protocol was exempt from approval from the regional ethics committee as stated by the national ethics committee (*Vejledning nr 11052 af 02/07/1999*). Nevertheless, the protocol adhered to the requirements of the Helsinki declaration. The participants involved were informed both in writing and orally about the project's purpose through the "Information to participants" letter (Appendix 1). Informed consent was gathered through a written consent form (Appendix 2). Furthermore, participants were informed that participation was voluntary and that they could withdraw their consent at any time. Anonymization through assigned ID numbers and no sensitive personal data was recorded. This protocol was reported to the Danish Patient Safety Authority via the University's umbrella agreement.

4. Results

4.1. Demographic data

Thirty participants (60 legs) entered the study. For a demographic description of participants, see Table 3.

Table 3 Demographic data of participants

	Age in years (SD)	Gender (%)	Weight in kg (SD)	Height in cm (SD)
Participants (n = 30)	27 (±3.5)	M 23 (76.6%) W 7 (23.3%)	82.8 (±15.9)	177.2 (±8.3)

Note: SD = Standard Deviation; M = Male; W = Woman; R = Right foot; L = Left foot

4.2. Reliability

4.2.1. *Intraclass Correlation Coefficient (ICC)*

The obtained ICC was generated across 60 subjects. The ICC values for MOTI were poor (ICC < 0.500), ranging from 0.269 – 0.491. The ICC values for the force platform showed some variability with poor reliability (ICC < 0.500) in FL and SL, and moderate reliability (0.500 < ICC > 0.750) in DL. ICC values are presented in Table 4.

4.2.2. *Minimal Detectable Change (MDC)*

A slight difference in MDC and SEM values was found between the MOTI and force platform for all movements. SEM and MDC values are presented in Table 4

Table 4 Test-retest reliability with MOTI and Force Platform

Modality	Trial 1 Mean (SD)	Trial 2 Mean (SD)	Trial 3 Mean (SD)	ICC	SEM	MDC^{95}
Force platform, FL	0.586 (0.223)	0.598 (0.220)	0.570 (0.169)	0.419	0.156	0.433
MOTI, FL	0.548 (0.229)	0.492 (0.152)	0.518 (0.221)	0.269	0.173	0.479
Force platform, SL	0.567 (0.176)	0.631 (0.248)	0.574 (0.200)	0.231	0.185	0.512
MOTI, SL	0.514 (0.204)	0.478 (0.185)	0.538 (0.207)	0.491	0.142	0.393
Force platform, DL	0.552 (0.145)	0.599 (0.211)	0.647 (0.249)	0.627	0.126	0.349
MOTI, DL	0.555 (0.170)	0.618 (220)	0.527 (0.284)	0.410	0.180	0.499

Note: FL = Forward Landing; SL = Sideways Landing; DL = Drop Landing; ICC = Intraclass Correlation Coefficients; SEM = Standard Error of Measurement; MDC = Minimal Detectable Change

4.3. Validity

4.3.1. *Intraclass Correlation Coefficient (ICC)*

The obtained ICC was generated across 60 subjects. However, the number of legs in the final analysis of ICC fluctuates because of an error in detecting TTS in some of the MOTI data. Compared to the force platform, the ICC values were poor (ICC < 0.500), ranging from 0.191 – 0.413. ICC values are presented in Table 5.

Table 5 ICC valued for mean MOTI data compared to mean Force platform data.

Modality	Force platform Mean (±SD)	MOTI Mean (±SD)	ICC
Forward landing (n = 51)	0.586 (0.139)	0.520 (0.170)	0.191
Side landing (n = 53)	0.588 (0.134)	0.500 (0.147)	0.206
Drop landing TTS (n = 56)	0.599 (0.157)	0.536 (0.167)	0.413

Note: TTS = Time to Stabilization; s = Seconds; LoA = Limit of Agreement

4.3.2. *Limit of Agreement (LoA)*

Mixed-method ANOVA analysis showed no significant systematic difference between MOTI and force platform in movements FL and DL tasks (FL: p-value = 0.052, df = 43) (DL: p-value = 0.059, df = 43). For SL, however, a significant difference was found between the modalities where the force platform recorded a significantly longer TTS for the force platform than MOTI (SL: p-value = 0.003, df = 43).

MOTI seemed to underestimate TTS in all tasks as compared to the force platform, as seen by a mean difference of 0.064 seconds (95% LoA = 0.415) for FL, a mean difference of 0.092 seconds (95% LoA = 0.368 s) for SL, and a mean difference of 0.067 seconds (95% LoA = 0.387 s) for DL (Figure 4).

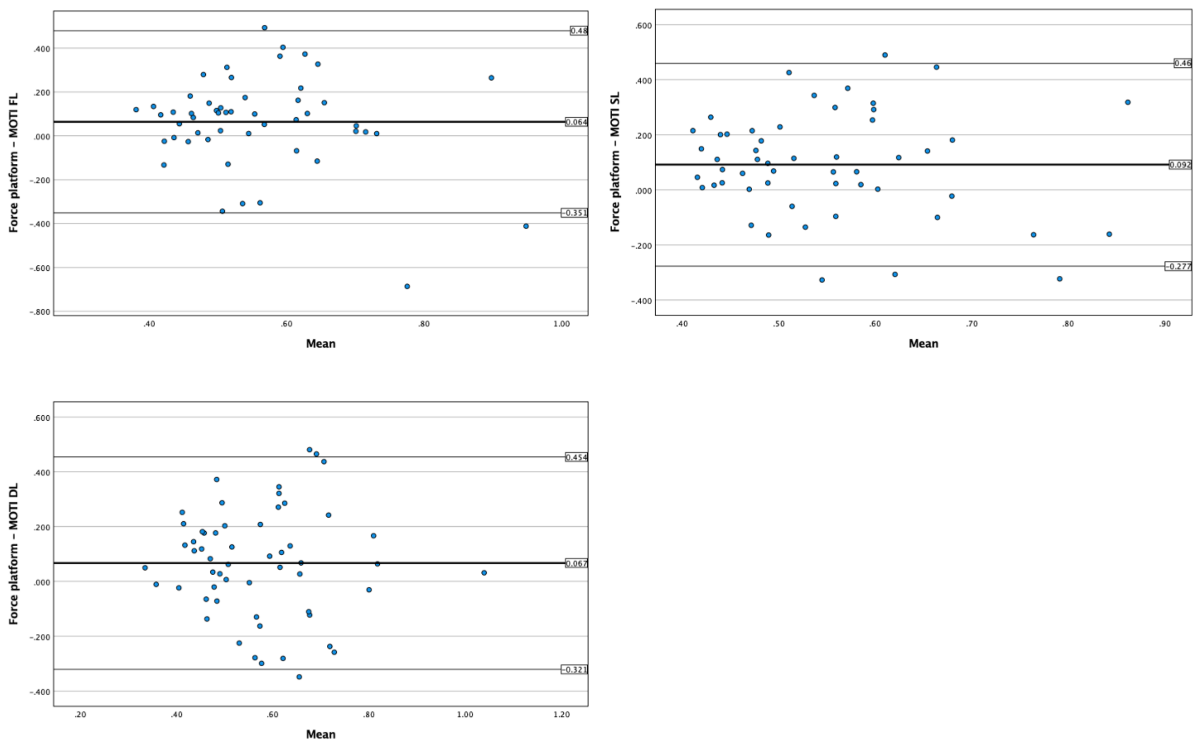

Figure 4 Bland Altman plot for Forward Landing, Sideways Landing, and Drop Landing. The solid black line represents the mean difference, and full lines represent the 95% LoA for the mean difference.

5. Discussion

The purpose of this study was to investigate the reliability and validity of MOTI by comparing measures of dynamic stability (TTS) on single-leg landings: Forward Landing, Sideways Landing, and Drop Landing objectively up against a force platform. This section will include a presentation of results, a critical discussion of reliability and validity, interpretation of the results in light of the existing literature. Finally, future perspectives possibilities for further development will be discussed.

5.1. Principal findings

The reliability of TTS measurements from MOTI lacks in tasks FL, SL, and DL, due to its low $ICC_{3.k}$, with values being < 0.500. ICC values of test-retest reliability show that the force platform is more reliable than MOTI in movements FL and DL. However, in movement SL, MOTI are more reliable in test-retest measurements. SEM and MDC values for MOTI show a slight difference in values in movements FL and DL compared to the force platform. However, there are opposite difference values of SEM and MDC in task SL, with MOTI having lower values of SEM and MDC. The validity of MOTI was assessed to be poor in all movements. Bland Altman plot showed that there is a slight underestimation and a wide variety of TTS measured on MOTI for all tasks.

5.2. Test-Retest reliability

It is difficult to determine whether the current results reflect findings elsewhere, as there do not seem to be any studies investigating the ability of single wearable sensors to measure dynamic stability of single-leg landings through TTS. The standardization of performance of each landing trial for each movement was challenging. This was seen through variances between trials for each participant (Table 4). The consequence of this was the poor test-retest reliability of MOTI and force platform. Because of this method, determining how consistent MOTI and force platform measurements were challenging through an analysis of ICC. The result showed poor reliability with every movement in MOTI (FL: ICC = 0.269; SL: ICC = 0.491; DL: ICC = 0.410) and force platform (FL: ICC = 419; SL: ICC = 231), however, there are an exception of poor test-retest ICC values in task DL (DL: ICC = 627) on the force platform. Furthermore, the results of reliability made the basis for the calculation of SEM and MDC values. Therefore, the high degree of SEM and MDC is a result of the high degree of uncertainty from a poor reliability score. This may indicate that if a patient is to be measured with MOTI on dynamic stability, one should account for the degree of SEM as measurement error and the MDC as the limit of when one can say actual changes of TTS have occurred. However, due to the relatively high MDCs (0.393 - 0.499 s) for TTS with MOTI, one could say that the level of MDC is relatively high considering the mean duration of TTS reported in Table 5. In other words, to detect a change of TTS on MOTI on the basis of the mean TTS reported in this report, a change from 0.5 s to 0.1 s would need to occur. However, baseline TTS may be longer in clinical groups than in this study, where only healthy individuals were measured. Therefore, it is possible that TTS are different in clinical groups (Webster, Kathryn A. & Gribble, 2010).

5.3. Validity

The validity of TTS measures in FL was found to be poor (ICC = 0.191). However, with the Bland Altman plot, there seems to be a slight, but non-significant underestimation of MOTI and that there is a large variability between the modalities (LoA = 0.415 s). Comparing this with other modalities that measure quality of control through wearable inertial sensors, where Al-Amri et al., (2018) found an excellent agreement in the sagittal plane and acceptable agreement in the frontal and transverse plane in the frontal and transverse planes of the hip, knee, and ankle joint angles.

A limited agreement was found in measures of TTS in task SL with a wide variability and a more considerable underestimation than for FL and DL (Figure 4). This is aligned with existing literature (Di Paolo et al., 2021), suggesting that movement complexity affects agreement between measurement devices. Moreover, SL movements are considered more complex than FL and DL, as indicated by a lower dynamic stability score in lateral movements than vertical and anterior movements (DuPrey et al., 2016; Sell, 2011).

DL presented itself with the highest degree of validity between the movements, with an ICC value (ICC = 0.413) close to be considered moderate (0.75 < ICC > 0.50). The Bland Altman plot presented a similar variability of agreement as other movements (Figure 4). This does not correlate with the level of agreement seen in Di Paolo et al. 2021, which investigates validity between a full-body suit of wearable inertial sensors compared to a 3D video analysis (Di Paolo et al., 2021).

5.4. Application of MOTI

To ensure future improvements in clinical practice, there is a potential for MOTI to be of use as a modality that applies only a single wearable inertial sensor and that it can assess the effect of strategy, which the individual uses when landing. Therefore, it may be possible that MOTI can be used to evaluating the output of joint kinematic analysis through measurements of TTS when there is absence of equipment needed for such evaluations. However, based on the result from this project, this can only be done when advances in the accuracy of TTS values measured with MOTI and a higher correlation of measures compared to a gold standard are present. When this is present, there can be advocacy for the use of MOTI in the rehabilitation of ACL and lower body injuries through the use of MOTI to provide a simple and accessible way of accurately measuring dynamic stability, and therefore be of importance to contribute to the clinical decisions and individualization of RTS with ACL injuries.

Nevertheless, with the limiting results in reliability and validity, there could be some limited use for MOTI in clinical practice as of now. As data indicate that the use of quantifying data as hop distance and symmetry does not give an adequate assessment of the performance of neuromuscular control. Therefore, could the implantation of MOTI be used as some indicator of progression when there is an absence of another ways of producing qualitative data of factors related to dynamic stability. Therefore, MOTI may contribute to some information that further support decision-making. However, to report a change with the results from this project, an MDC is set to be 0.479 s in FL, 0.393 s in SL, and 0.499 s in DL. This makes that relative high change should occur to be able to report any real change. Therefore, the use of MOTI would only be reasonable in a clinical population, where higher TTS values may present themselves. The use of MOTI as a preventative measure to indicate any deficits in dynamic stability in healthy individuals is therefore not advised.

5.5. Limitations and methodological refinement

In this project, the velocity/intensity of the jumps onto the force platform was not controlled for or standardization for in any other ways than the distance from start point to the center of the platform. Even though each participant was instructed to perform jumps in a similar manner, some differences were observed between trials amongst the participants when instructed to jump onto the force platform (Table 4). This control of velocity has been standardized in other studies studying dynamic stability where a hurdle of 30 cm was placed in front in movement FL and besides in the SL movement (Head et al., 2019; Heinert et al., 2018). This lack of ways to standardize the execution of each jump could be a contributing factor to the difference in reliability in movements. This can be seen in movement DL, which was the only movement with a standardized height that the participants should drop from, thereby controlling the velocity for each attempt, while in FL and SL, this was missing.

The last limitation which might influence the results is the placement of MOTI. As MOTI was placed on the lower back. It could be argued that MOTI detects, e.g., trunk and hip strategies which the force platform does measure to a lesser degree as it is located directly below the base of support. This may have affected the reliability and validity of this project, as it may be that the force platform is more sensitive to lower leg strategies for dynamic stability, and MOTI being more sensitive to hip and trunk strategies for dynamic stability.

5.6. Recommendations for future studies

Future studies could include a hurdle or other equipment to control the performance in a more standardized fashion. In addition, it could be interesting to introduce an extra level of velocity and investigate further whether MOTI can detect differences in TTS with higher velocities. Further investigations in clinical groups could give insight into MOTI's ability to sense changes in TTS that may present themself in the performance of FL, SL, and DL in clinical groups, e.g., individuals with an ACL injury. Therefore, studies that compare participants with a previous ACL injury/undergone an ACL-R with healthy adults could be of interest. In addition, it could give further insight into the investigation of progression of TTS during rehabilitation after an ACL injury. This could give insight into baseline values of TTS with healthy participants compared to the target group of persons with an ACL injury. Lastly, due to the limitation of the location of MOTI compared to the force platform, it could be of interest to examine different placement locations of MOTI, e.g., at the thigh or knee and thereby being closer to the base of support and compare these findings to the force platform.

6. Conclusion

The MOTI device is not a reliable and reliable substitute for expensive and advanced equipment to evaluate dynamic stability through TTS in single-leg landings. The application of MOTI in clinical situations might only be to contribute to the assessment of progression in single-leg landings. However, due to the limitations of MOTI, this use should not stand alone and could only act as an addition to the evaluation when no better alternative is present. Therefore, could the values from MOTI contribute in a limited fashion to the clinical decision-making and individualization of rehabilitation processes. However, assessment of single-leg landing through the use of MOTI should not stand-alone to evaluate dynamic stability as this project does not produce reliable and valid TTS values compared to a force platform.

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