



Research article

Lower extremity range of motion and alignment: A reliability and concurrent validity study of goniometric and three-dimensional motion analysis measurement

Viktor Ore^{a,*}, Salmir Nasic^b, Jacques Riad^{c,d}^a Dept of Orthopedics, Skaraborg Gait Analysis Laboratory, Skaraborg Hospital Skövde, Lövängsgatan 1, 541 85, Skövde, Sweden^b Research and Development Centre, Skaraborg Hospital, Skövde, Sweden^c Dept of Orthopedics, Institute of Clinical Science, Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden^d Dept of Orthopedics, Skaraborg Hospital, Skövde, Sweden

ARTICLE INFO

Keywords:

Anatomy
 Clinical research
 Rehabilitation
 Diagnostics
 Health promotion
 Health technology
 Goniometer
 Three-dimensional motion analysis
 Reliability
 Concurrent validity
 Knee injury
 Anterior cruciate ligament rupture

ABSTRACT

Background: Knowing correlations between passive goniometric and dynamic three-dimensional motion analysis measurements of lower extremity range of motion and alignment would benefit knee injury risk assessment.

Purpose: To investigate reliability and concurrent validity of lower extremity assessment with goniometry and three-dimensional motion analysis.

Methods: Thirty-eight participants (76 limbs) were examined in standardized positions by two physiotherapists with simultaneous goniometric and three-dimensional motion analysis measurements of passive range of motion and alignment. Intra-class correlation coefficient (ICC) and median differences were calculated.

Results: Hip rotation reliability, ICC 0.74–0.89 and validity 0.74–0.94. Tibial rotation reliability, ICC 0.24–0.75 and validity 0.08–0.61. Knee extension reliability, ICC 0.44–0.73 and validity 0.22–0.60. Knee valgus/varus reliability, ICC 0.36–0.68 and validity 0.25–0.62. Tibial torsion reliability, ICC 0.52–0.77 and validity 0.58–0.81. Ankle dorsiflexion reliability, ICC 0.12–0.73 and validity 0.51–0.83. Median differences in reliability and validity ranged from -2.0° to 3.0° and from -6.6° to 7.5° respectively.

Conclusion: Goniometric and three-dimensional motion analysis methods define the lower body segments differently making some degree of discrepancy in the measurements inevitable. Nevertheless, the variables chosen in this study are all strongly associated with anterior cruciate ligament rupture and some may prove useful to identify individuals at risk of knee injury during sport activities.

Study design: Cross-sectional laboratory study.

1. Introduction

The use of reliable and valid measurements is crucial in clinical practice and in research. Physical examination is often performed to assess anatomical characteristics, such as passive range of motion (PROM) and alignment of the lower extremity, and a goniometer is used to quantify the measurements [1]. To capture motion in dynamic tasks such as walking and jumping, a three-dimensional motion analysis (3D MA) is usually performed [2, 3, 4]. It can be challenging to obtain reliable and valid data about fast movements and high forces e.g. in sport activities [5, 6, 7, 8]. Physical examination and 3D MA assessment are used when studying the biomechanics and risk factors associated with rupture of the anterior cruciate ligament (ACL) [9, 10, 11, 12, 13]. This risk is

associated with increased knee extension, knee valgus, and tibial rotation in relation to the femur, and with decreased ankle dorsiflexion and hip internal rotation, as measured with a goniometer [14, 15, 16, 17, 18]. During dynamic activities, increased knee valgus at initial landing in the vertical drop jump, assessed by 3D MA, has been reported to increase the risk of ACL rupture [19].

The reliability of goniometric measurements of PROM in the lower extremity is considered to be good to excellent, although a mean standard deviation (SD) of around 5° has been reported for repeated measures in inter-observer studies [1]. The validity of the measurements compared to “gold standard” radiographic measurements of the knee joint is good to excellent [1]. An exception is tibial rotation measured with an inclinometer, a goniometer for rotational assessment [20]. One disadvantage

* Corresponding author.

E-mail addresses: Viktor.ore@vgregion.se, oreviktor@gmail.com (V. Ore).<https://doi.org/10.1016/j.heliyon.2020.e04713>

Received 18 May 2020; Received in revised form 26 June 2020; Accepted 10 August 2020

2405-8440/© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

of ordinary hand-held inclinometers is that the tibial rotation is measured at the foot level, thus including some motion at the foot-ankle, and not exclusively in the tibio-femoral joint [21]. Inclinometers attached to the tibia, such as the Myrin goniometer used in this study, have the advantage of specifically measuring tibial rotation in relation to the femur. However, the Myrin goniometer has not been thoroughly tested for reliability [1, 22].

The reliability of dynamic measurements with 3D MA on subjects performing various jump tests is considered good [7, 23, 24]. The quality of the 3D MA assessments is highly dependent on marker placement, which is reported to be especially difficult around the knee joint [6, 25, 26, 27, 28]. The validity of 3D MA has seldom been assessed, probably due to the complexities of quantifying dynamic motion. However, Miranda et al compared results obtained with 3D MA versus advanced bi-planar radiography, which makes it possible to measure “true” joint motion in dynamic activities, and found that skin movement during jumps involving high velocity and impact adds another limitation to 3D MA [6]. Despite limitations, 3D MA is still considered the “gold standard” for quantifying dynamic motion and is frequently used both in clinical practice and in research [4, 23, 29].

Although radiographic measurement is considered more precise than goniometric and 3D MA assessments, it is expensive, inaccessible, exposes subjects to radiation, and is difficult to use for multiple joints simultaneously [1, 6]. Consequently, goniometric and 3D MA assessments are better suited, than radiographic measurements, for clinical and research purposes, although the limitations must always be taken into consideration.

The association between goniometric and 3D MA assessment has not been thoroughly studied. It has been suggested that exceeding the anatomical range of motion or alignment during a dynamic activity such as jumping or performing a side-cut maneuver may lead to injury [30, 31]. When attempting to understand injuries associated with sports, it could be of interest to compare goniometric and 3D MA measurements. If lower extremity range of motion and alignment corresponds between goniometric and 3D MA measurements, and evidence of high forces assessed with 3D MA are associated with movement beyond anatomical limitations measured in a goniometric assessment, this might possibly explain the mechanism underlying ACL rupture.

The reliability and validity of goniometric and 3D MA assessments of the lower extremity have been studied separately. However, to our knowledge, the only two studies examined both types of assessment simultaneously during physical activity reported varied results for muscle length end-angles in the lower extremity and an overestimated shoulder elevation by goniometer by 20° compared to 3D MA [32, 33]. However, a related study reported good to excellent concurrent validity between 3D MA and a bubble inclinometer for hip joint PProM [34]. An understanding of the agreement and potential measurement errors for

different variables in the physical examination is crucial. When making comparisons between two different methods, in this case static anatomical versus dynamic measurement, it is important to keep in mind that they will generate different results [32].

1.1. Purpose

The purpose was to study reliability and concurrent validity of assessment of passive range of motion and alignment of the lower extremity using a goniometer and a three-dimensional motion analysis system.

2. Materials and methods

A repeated measures design was used in this cross-sectional laboratory study. Ethical committee approval (Gothenburg regional ethical committee, ref 094-17) was obtained and all participants gave informed consent in writing.

2.1. Procedure

From the medical record and diagnosis register at Skaraborg Hospital Skövde from 2012 to 2018, individuals between 18 and 25 years of age with ACL rupture were identified for the purpose of this study. Information and an invitation to participate was sent by mail to 182 individuals. Forty-two who indicated interest in participating were contacted for more information and checked for eligibility. Ultimately, 38 participants were recruited.

When examined at the gait laboratory, the participants were barefoot and wore shorts. All assessments were performed by two experienced physiotherapists, whom before the study had practiced and discussed the execution of each measurement to ensure the standardization of the test conditions. For the inter-observer reliability study, each physiotherapist independently performed physical examinations in standardized positions according to the literature [1, 22, 35, 36, 37].

For the concurrent validity study, physiotherapist 1 (author VO) applied the markers and positioned the joint at end-range of motion, whereafter physiotherapist 2 (A-LW) obtained the measure with a goniometer. At the same time physiotherapist 1 gave a signal making sure the joint position was recorded with the 3D MA system. With other words the measurement with the goniometer was performed simultaneously with the 3D acquisition. End-range of motion was defined as when resistance was felt by the physiotherapist and further motion caused co-movement of adjacent joints [1, 22]. No force was applied during alignment assessment [35, 36, 37]. This procedure was used for all measurements except sitting tibial rotation, which physiotherapist 1 measured without assistance. The assessments were done in the same order for all

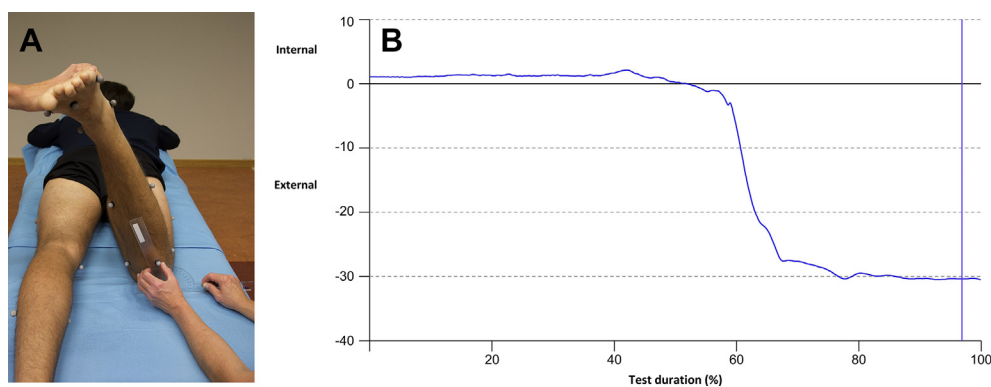


Figure 1. A: Assessment with goniometer and marker-based three-dimensional motion analysis of hip external rotation with extended hip in the concurrent validity study. B: Graph from the three-dimensional motion analysis of hip external rotation with extended hip. Motion (degrees) on the y-axis and test duration (percent) on the x-axis. In this case the resting angle is around zero and then at about 55% of the test duration, the hip is moved into external rotation, at around 30°.

participants and limbs. Measurements were taken in supine, prone and finally sitting position.

2.2. Goniometric assessments

One universal 31-centimeter plastic 180° goniometer was used for most range of motion measurements (Vinkelmätare Brodin, Medema Physio AB, Kista, Sweden). For foot and tibial alignment measurements we used a 17-centimeter plastic 360° universal goniometer (Plastic goniometer 360, DJO Global, Dallas, USA). To measure passive tibial rotation, an inclinometer (Myrin goniometer, Parir AB, Bålsta, Sweden) was used. Figures 1A, 2A and 3.

2.3. Three-dimensional motion analysis assessment

A three-dimensional motion analysis system incorporating 30 reflective markers and 12 digital cameras (Oqus 400 Qualisys medical AB, Gothenburg, Sweden) was used. A marker-based biomechanical model was chosen and the reflective markers were secured to specific anatomical locations in accordance with a modified Liverpool John Moore University biomechanical model (LJMU-model) [5]. The modification consisted of additional markers for tuberositas tibiae and the head of metatarsal 2, an extra cluster marker at the medial side of the shank, one instead of four cluster markers at the lateral shank and thigh and no marker for greater trochanter nor upper body. Figures 1A, 2A and 3.

2.4. Variables assessed

The variables chosen were those previously reported as potentially associated with the risk of ACL rupture: hip rotation, passive tibial rotation, knee extension, knee valgus/varus assessed by the tibio-femoral angle (TFA), tibial torsion assessed with the bi-malleolar angle (BMA) and ankle dorsiflexion [9, 10, 11, 12, 14, 15, 16, 18, 19].

Hip external and internal rotation was obtained with flexed hip joint in supine and with extended hip joint in prone position. Tibial rotation relative to the femur was measured in sitting position. Knee extension and ankle joint dorsiflexion with extended and flexed knees, were examined in supine position. The knee valgus/varus angle (i.e. the TFA) was measured in the frontal plane and positive values were used to indicate valgus position. Tibial torsion was assessed by the bi-malleolar angle (BMA) and obtained in prone position [1, 22, 35, 36, 37].

2.5. Statistics

Descriptive statistics as mean and standard deviation were calculated and presented for all continuous variables. The histogram graphs for all continuous variables were observed visually and Shapiro-Wilks test were performed to assess whether variables were approximately normally distributed. Intra-class correlation coefficient (ICC) with a two-way random effects model with definition consistency and type single measures was used to explore and calculate inter-observer reliability and concurrent validity for all continuous variables. 95% confidence interval

for ICC was presented. The difference between related observations for each variable were described and quantified as the median difference with quartile range (q1; q3). All analyses were performed with the statistical package IBM SPSS version 25.

3. Results

The participants were 27 women and 11 men, mean age 21.4 (SD 2.3) years, mean height 173.4 (SD 8.5) cm and weight 74.7 (SD 11.1) kg, participated.

One of the 3D MA assessments could not be processed due to technical problems and could not be included in the validity study. In four cases, tibial rotation could not be fully assessed due to markers being hidden.

3.1. Inter-observer reliability of goniometry

The ICC values for the inter-observer study were 0.83–0.84 for hip rotation measurements. The ICC was 0.54–0.66 for tibial external rotation, knee extension, knee valgus/varus (TFA), tibial torsion (BMA) and ankle dorsiflexion with extended knee. Lower ICC values < 0.5 were noted for tibial internal rotation and ankle dorsiflexion with flexed knee. The median differences of measurements were within a few degrees for all measures (range -2.0°–3.0°). Table 1.

3.2. Concurrent validity between goniometry and 3D MA

The ICC values in the validity study were 0.83–0.91 for hip rotation, 0.72 for tibial torsion (BMA), 0.66 to 0.74 for ankle dorsiflexion and <0.5 for knee extension, knee valgus/varus (TFA) and tibial rotation. The median differences of single measurements were for hip rotation -3.6°–5.0°, tibial rotation 5.1°–7.5°, knee extension -2.4°, knee valgus/varus (TFA) 2.6°, tibial torsion (BMA) -1.5° and ankle dorsiflexion -6.6° to -5.7°. Table 2.

4. Discussion

The intra-class coefficient (ICC) values for both inter-observer reliability and concurrent validity were highest for hip rotation whereas those for measurements in the knee and ankle joint were lower.

The median differences were higher for concurrent validity (range -6.6°–7.5°) than for inter-observer reliability (median values close to 0°, range -2.0°–3.0°), meaning that discrepancies between goniometric and 3D MA assessments tended to be larger than those between goniometric assessments.

4.1. Reliability and validity

Koo and Li suggested a guideline for interpretation of ICC in which values under 0.5 indicated poor reliability, values between 0.5 and 0.75 moderate, values between 0.75 and 0.9 good, and values exceeding 0.9 excellent reliability; they also stressed the importance of presenting the 95% confidence interval (CI) [38].

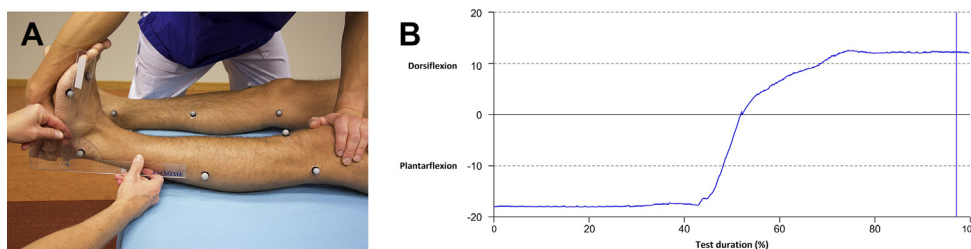


Figure 2. A: Assessment with goniometer and marker-based three-dimensional motion analysis of ankle dorsiflexion with extended knee in concurrent validity study. B: Graph from the three-dimensional motion analysis of ankle dorsiflexion with extended knee. Motion in degrees on the y-axis and test duration on the x-axis. In this case the resting angle is around 18° plantar flexion and then at about 45% of the test duration the ankle is moved into dorsiflexion to a maximum of around 12°.

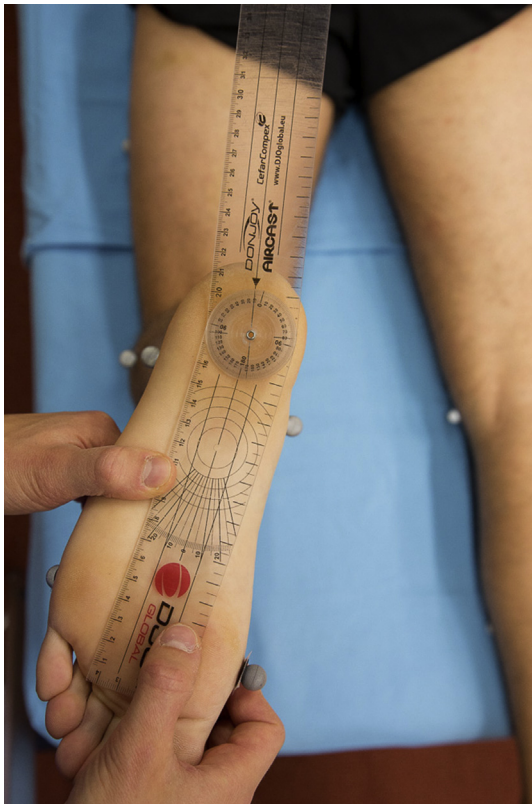


Figure 3. Goniometer and marker-based three-dimensional motion analysis assessment of tibial torsion. The markers on the medial and lateral malleolus are visualized for the acquisition of the bi-malleolar angle, which is calculated in relation to the knee axis.

Our results showing good inter-observer reliability for goniometric measurements of passive *hip rotation* are in line with the findings of Norkin and White [1]. Concurrent validity was good to excellent, which was in line with previous reported results by Charlton et al, albeit they used a bubble inclinometer and another position for measurement [34]. Hip rotation influences knee position and thereby muscle activity and forces affecting the knee during jumping activities [39, 40]. Hip rotation

is part of the mechanism causing dynamic valgus collapse that might result in an ACL rupture [39]. It should be noted that the effect of hip rotation is mixed: some studies report that individuals with decreased hip internal rotation have an increased risk of ACL rupture [14, 15, 17], whereas other studies using 3D MA show markedly higher knee forces for individuals with increased hip internal rotation [11, 12]. Our findings of good reliability and validity make the assessments comparable, which could potentially be useful in further studies aiming to identify specific thresholds that imply a higher risk of injury.

Passive *tibial rotation* assessment revealed poor to moderate reliability in our study, and using a Myrin goniometer attached to the tibia gave no advantage compared to methods measuring tibial rotation at the foot, e.g. as used by Krause et al [20]. To further improve the accuracy, technically advanced equipment has been developed; however, this equipment is clumsy and not clinically applicable [18, 41, 42]. In our study, concurrent validity for tibial rotation was poor to moderate. Olsen et al reported knee rotation as an important variable for the risk of ACL rupture, but they do not state whether it is internal or external rotation both [43]. Oh et al stated that the combination of knee internal rotation and knee valgus results in increased strain on the ACL during pivoting landing [44]. Given the poor reliability and validity shown by our results, we do not know how to make clinically applicable assessments to help understand the degree of tibial rotation that could be associated with ACL rupture.

Goniometric assessments of *knee extension* revealed poor to moderate reliability in our study, in line with the low reliability presented by Norkin and White (inter-observer ICC 0.57 to 0.80) [1]. The low ICC value might be explained by our use of a single measurement ICC method, which is more prone to measurement errors than other methods. Since knee extension is of small angles (normal range 0°–10°), measurement errors of a couple of degrees have a much stronger negative impact on ICC values compared to values for, e.g., the hip joint (normal range 40°–60°) [1]. Concurrent validity was poor to moderate, which might partly be explained by the same factors. Myer et al reported that increased knee extension could contribute to increased risk of sustaining an ACL rupture, making this variable important [16]. Though our results revealed poor to moderate ICC values, the rather small median differences (1.0° inter-observer reliability, -2.4° concurrent validity) indicated that knee measurements might be compared if measurement error is considered.

Knee valgus/varus (TFA) assessment revealed poor to moderate reliability, in contrast to the good to excellent inter-observer values reported by Schultz et al [37]. Schultz et al used a goniometer with extended arms

Table 1. Inter-observer reliability of goniometric assessments of passive range of motion and alignment in 76 lower extremities (38 subjects).

N = 76	Observer 1 Mean° (SD°)	Observer 2 Mean° (SD°)	ICC (95% CI)	Median difference (q1°; q3°)
Hip				
Hip external rotation 90° flexed hip	55.9 (7.0)	53.2 (7.5)	.83 (.74–.89)	3.0 (0.3; 5.8)
Hip internal rotation 90° flexed hip	40.6 (9.7)	40.4 (8.4)	.83 (.75–.89)	0.0 (-3.8; 4.8)
Hip external rotation extended hip	47.9 (6.9)	48.4 (7.5)	.84 (.75–.89)	-1.0 (-3.0; 3.0)
Hip internal rotation extended hip	42.3 (8.9)	42.4 (9.4)	.84 (.75–.89)	0.0 (-4.0; 3.0)
Knee				
Tibial external rotation	28.9 (4.1)	29.1 (5.6)	.63 (.47–.75)	0.0 (-3.0; 2.0)
Tibial internal rotation	26.4 (4.1)	26.0 (4.1)	.44 (.24–.61)	0.5 (-3.0; 4.0)
Knee extension	7.0 (2.7)	5.9 (2.6)	.61 (.44–.73)	1.0 (-2.0; 4.0)
Knee valgus/varus (TFA)	5.7 (1.6)	4.3 (1.7)	.54 (.36–.68)	2.0 (0.0; 2.0)
Tibial torsion (BMA)	18.7 (4.9)	18.2 (4.4)	.66 (.52–.77)	0.0 (-2.0; 4.0)
Ankle				
Ankle dorsiflexion 90° flexed knee	17.6 (3.5)	17.3 (4.3)	.34 (.12–.52)	0.3 (-2.0; 4.0)
Ankle dorsiflexion extended knee	12.8 (3.4)	11.8 (4.2)	.61 (.44–.73)	1.0 (-1.0; 4.0)

SD: standard deviation; ICC: Intra-class correlation coefficient; CI: confidence interval, TFA: tibio-femoral angle; BMA: bi-malleolar angle.

and calculated ICC by using averages of measurements which might explain some of the differences in the results [37]. We found poor to moderate concurrent validity. As discussed for the knee extension measurements, the small angles of knee valgus/varus might contribute to the poor reliability and validity [1]. Knee valgus/varus is a measurement of interest since valgus/varus has been reported as directly involved in the injury mechanism for ACL ruptures, and an increased valgus at landing is associated with greater risk of ACL rupture [2, 19].

For *tibial torsion* (BMA) we found moderate to good reliability. Our median difference for alignment measures of BMA (0.0° q1; -2.0° q3; 4.0°) was in line with or lower than previously reported mean differences (3.2°) [35]. Concurrent validity was moderate to good. Ishida et al studied the impact of foot positioning with toe out or in, on knee rotation and valgus, without measuring tibial torsion [45]. Nor was tibial torsion discussed as a cofactor in studies reporting that foot placement at initial landing affects knee forces during jumping activities [40, 46, 47, 48]. In our study on reliability and validity we wanted to include the anatomical alignment of tibial torsion, since we believe it is reasonable to assume that tibial torsion and alignment with the knee axis influence foot position and hence knee rotation and knee forces.

The reliability of measurements of *ankle dorsiflexion* with extended knee in our study was in line with that in a previous report, ICC 0.61 and 0.65 respectively [1]. On the other hand, our measurements of ankle dorsiflexion with flexed knee had markedly lower reliability, ICC 0.34. One could assume that the amount of force that can be applied varies from examiner to examiner, and this has previously been discussed as a cause of low reliability [49]. However, the strong gastrocnemius muscle, which passes not only the ankle but also the knee joint, is relaxed when the knee is flexed and less force is likely to be required to measure ankle dorsiflexion, thus probably reducing the variability between examiners.

However, previous studies have pointed out that it is difficult for a single observer to measure dorsiflexion with flexed knee, which may partly explain the relatively low reliability [50]. Concurrent validity was moderate to good, and our ICC-values are in line with reported spearman correlation coefficients reported by Banky et al [33]. The mean and median differences between the methods revealed that 3D MA tended to give greater dorsiflexion compared to goniometry. Fong et al suggested that greater passive range of ankle dorsiflexion might reduce the forces affecting the ACL during landing [10]. Our results might be of importance in further studies aiming to find the degree of ankle dorsiflexion that is associated with higher forces affecting the ACL.

4.2. Association goniometric and 3D MA assessment

Our results revealed ICC values ranging from poor to excellent for measurements of different joints. One interpretation could be that hip rotation measurements are comparable between the different assessment methods and knee measurements are not. However, our comparison of mean and median differences between measurements revealed interesting details. For example, though hip internal rotation with 90° flexed hip had good to excellent ICC values, the median difference was 5.0° between assessment methods, whereas knee valgus/varus had poor to moderate ICC values but a median difference of 2.6°. Understanding the association between angle measurements obtained using the different assessments methods would be necessary to further study the forces affecting a joint when anatomical range of motion is exceeded.

Our results revealed that the mean and median differences between goniometric and 3D MA assessments, in degrees, were higher than the inter-observer differences in corresponding goniometric measurements. Although our differences were not as prominent as those presented by Finley et al [32] regarding shoulder elevation, our results provide insight into the off-set that should be considered when comparing goniometric measurements with those obtained with 3D MA.

This study was done in our clinical setting, using a marker-based biomechanical model and universal goniometers, and it must be borne in mind that the results are of relevance only in comparison to similar settings. However, since the segments in the lower extremity are defined differently for the different assessment methods – goniometry and 3D MA – it is fair to assume that measurement differences are inevitable regardless of which types of goniometers and biomechanical models are used. Hence, we recommend that future studies aiming to compare results from goniometry and 3D MA include tests of concurrent validity of the different measurement methods.

4.3. Limitations

The results of goniometric measurement of the long axis, i.e. knee valgus/varus (TFA), might have been more accurate if a goniometer with longer arms had been used.

Inter-observer reliability was likely affected by differences in the amount of force applied, especially in ankle dorsiflexion, where force has an impact on measured end-range of motion.

Marker placement is undoubtedly a limitation in the 3D MA assessment method. However, in our study, all markers were placed according

Table 2. Concurrent validity of goniometric assessment and 3D motion analysis assessment of passive range of motion and alignment in 74 lower extremities (37 subjects).

	N	Goniometer assessment Mean° (SD°)	3D motion analysis assessment Mean° (SD°)	ICC (95% CI)	Median difference° (q1°; q3°)
Hip					
Hip external rotation 90° flexed hip	74	58.9 (7.1)	62.5 (7.5)	.83 (.74–.89)	-3.6 (-6.7; -0.1)
Hip internal rotation 90° flexed hip	74	41.3 (9.0)	36.2 (8.8)	.89 (.83–.93)	5.0 (2.3; 7.3)
Hip external rotation extended hip	74	48.3 (7.0)	43.8 (7.7)	.84 (.76–.90)	3.8 (2.1; 5.9)
Hip internal rotation extended hip	74	41.7 (8.6)	39.3 (8.5)	.91 (.85–.94)	2.9 (-0.1; 5.1)
Knee					
Tibial external rotation	71	28.9 (3.4)	23.6 (6.1)	.44 (.23–.61)	5.1 (1.9; 9.4)
Tibial internal rotation	73	26.3 (3.6)	19.0 (6.0)	.30 (.08–.49)	7.5 (3.7; 11.6)
Knee extension	74	7.1 (3.3)	9.1 (3.8)	.43 (.22–.60)	-2.4 (-4.5; 0.9)
Knee valgus/varus (TFA)	74	4.3 (2.0)	1.4 (2.7)	.46 (.25–.62)	2.6 (1.4; 4.3)
Tibial torsion (BMA)	74	18.6 (5.0)	20.1 (6.4)	.72 (.58–.81)	-1.5 (-4.6; 0.7)
Ankle					
Ankle dorsiflexion 90° flexed knee	74	20.6 (5.2)	26.7 (5.9)	.74 (.61–.83)	-6.6 (-8.8; -3.7)
Ankle dorsiflexion extended knee	74	10.4 (4.1)	16.1 (6.5)	.66 (.51–.77)	-5.7 (-8.6; -2.7)

SD: standard deviation; ICC: Intra-class correlation coefficient; CI: confidence interval, TFA: tibio-femoral angle; BMA: bi-malleolar angle.

to a standardized placement protocol, by the same experienced physiotherapist, in line with suggested methods to reduce marker placement variability [23, 24].

5. Conclusion

The goniometric and three-dimensional motion analysis (3D MA) methods define the lower body segments differently, making some amount of difference/off-set between the measurement results essentially inevitable. The mean and median differences between results obtained using the goniometric and 3D MA methods were larger than the inter-observer differences in results obtained by goniometry, indicating that care should be taken when comparing results from the goniometer with 3D MA. In future studies it could be recommended to assess the methods' concurrent validity in the chosen specific clinical setting. The biomechanical variables of range of motion and alignment chosen for this study, in addition to being easy to assess clinically, are all strongly associated with anterior cruciate ligament rupture. Some could prove useful to identify individuals at risk of knee injury during sport activities.

Declarations

Author contribution statement

V. Ore: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

J. Riad: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

S. Nasic: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work was supported the governmental Skarborg Hospital Orthopedic Department and the Research and Development Center.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

Anna-Lena Wettterteg and Alexander Andersson for the work with acquisition of data in the Gait Analysis Laboratory.

References

- C.C. Norkin, D.J. White, *Measurement of Joint Motion : a Guide to Goniometry*, F.A. Davis, Philadelphia, 2009.
- K.R. Ford, G.D. Myer, T.E. Hewett, Valgus knee motion during landing in high school female and male basketball players, *Med. Sci. Sports Exerc.* 35 (10) (2003) 1745–1750.
- E. Kristianslund, T. Krosshaug, Comparison of drop jumps and sport-specific sidestep cutting: implications for anterior cruciate ligament injury risk screening, *Am. J. Sports Med.* 41 (3) (2013) 684–688.
- J. Perry, J.M. Burnfield, *Gait Analysis : normal and Pathological Function*, SLACK, Thorofare, N.J., 2010.
- B. Malfait, S. Sankey, F. Raja, R.M. Azidin, K. Deschamps, J. Vanrenterghem, M.A. Robinson, et al., How reliable are lower-limb kinematics and kinetics during a drop vertical jump? *Med. Sci. Sports Exerc.* 46 (4) (2014) 678–685.
- D.L. Miranda, M.J. Rainbow, J.J. Crisco, B.C. Fleming, Kinematic differences between optical motion capture and biplanar videoradiography during a jump-cut maneuver, *J. Biomech.* 46 (3) (2013) 567–573.
- G.D. Myer, N.A. Bates, C.A. DiCesare, K.D. Barber Foss, S.M. Thomas, S.C. Wordeman, et al., Reliability of 3-dimensional measures of single-leg drop landing across 3 institutions: implications for multicenter research for secondary ACL-injury prevention, *J. Sport Rehabil.* 24 (2) (2015) 198–209.
- S.P. Sankey, R.M. Raja Azidin, M.A. Robinson, B. Malfait, K. Deschamps, S. Verschueren, et al., How reliable are knee kinematics and kinetics during side-cutting manoeuvres? *Gait Posture* 41 (4) (2015) 905–911.
- A.D. Nguyen, S.J. Shultz, R.J. Schmitz, Landing biomechanics in participants with different static lower extremity alignment profiles, *J. Athl. Train.* 50 (5) (2015) 498–507.
- C.M. Fong, J.T. Blackburn, M.F. Norcross, M. McGrath, D.A. Padua, Ankle-dorsiflexion range of motion and landing biomechanics, *J. Athl. Train.* 46 (1) (2011) 5–10.
- A. Nguyen, J. Cone, L. Stevens, R. Schmitz, S. Shultz, Influence of hip internal rotation range of motion on hip and knee motions during landing, *J. Athl. Train.* 44 (suppl) (2009) S68.
- J. Riad, K. Hjältman, S. Coleman, Lower limb alignment in young female athletes is associated with knee joint moments during the drop vertical jump, *Arch. Sports Med. Physiother.* 2 (1) (2018) 21–25.
- S.M. Sigward, S. Ota, C.M. Powers, Predictors of frontal plane knee excursion during a drop land in young female soccer players, *J. Orthop. Sports Phys. Ther.* 38 (11) (2008) 661–667.
- D. Amraee, M.H. Alizadeh, H. Minoonejad, M. Razi, G.H. Amraee, Predictor factors for lower extremity malalignment and non-contact anterior cruciate ligament injuries in male athletes. Knee surgery, sports traumatology, arthroscopy, offic. *J. ESSKA* 25 (5) (2017) 1625–1631.
- A. Bedi, R.F. Warren, E.M. Wojtys, Y.K. Oh, J.A. Ashton-Miller, H. Oltean, et al., Restriction in hip internal rotation is associated with an increased risk of ACL injury, *Knee Surg. Sports Traumatol. Arthrosc. : offic. J. ESSKA* 24 (6) (2016) 2024–2031.
- G.D. Myer, K.R. Ford, M.V. Paterno, T.G. Nick, T.E. Hewett, The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes, *Am. J. Sports Med.* 36 (6) (2008) 1073–1080.
- C. VandenBerg, E.A. Crawford, E. Sibilsky Enselman, C.B. Robbins, E.M. Wojtys, A. Bedi, Restricted hip rotation is correlated with an increased risk for anterior cruciate ligament injury, *Arthroscopy : J. Arthrosc. Relat. Surg Offic. Publ. Arthrosc. Assoc. N. Am. Int. Arthrosc. Assoc.* 33 (2) (2017) 317–325.
- T.P. Branch, J.E. Browne, J.D. Campbell, R. Siebold, H.I. Freedberg, E.A. Arendt, et al., Rotational laxity greater in patients with contralateral anterior cruciate ligament injury than healthy volunteers, *Knee Surg. Sports Traumatol. Arthrosc. : offic. J. ESSKA* 18 (10) (2010) 1379–1384.
- T.E. Hewett, G.D. Myer, K.R. Ford, R.S. Heidt Jr., A.J. Colosimo, S.G. McLean, et al., Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study, *Am. J. Sports Med.* 33 (4) (2005) 492–501.
- D.A. Krause, B.A. Levy, J.P. Shah, M.J. Stuart, J.H. Hollman, D.L. Dahm, Reliability of the dial test using a handheld inclinometer, *Knee Surg. Sports Traumatol. Arthrosc. : offic. J. ESSKA* 21 (5) (2013) 1011–1016.
- M. Alam, A.M.J. Bull, R. Thomas, A.A. Amis, Measurement of rotational laxity of the knee: in vitro comparison of accuracy between the tibia, overlying skin, and foot, *Am. J. Sports Med.* 39 (12) (2011) 2575–2581.
- H.M. Clarkson, *Musculoskeletal Assessment : Joint Range of Motion and Manual Muscle Strength*, Lippincott Williams & Wilkins, Philadelphia, 2000.
- K.R. Ford, G.D. Myer, T.E. Hewett, Reliability of landing 3D motion analysis: implications for longitudinal analyses, *Med. Sci. Sports Exerc.* 39 (11) (2007) 2021–2028.
- K.M. Mok, E. Petushek, T. Krosshaug, Reliability of knee biomechanics during a vertical drop jump in elite female athletes, *Gait Posture* 46 (2016) 173–178.
- E. Szczerbik, M. Kalinowska, The influence of knee marker placement error on evaluation of gait kinematic parameters, *Acta Bioeng. Biomech.* 13 (3) (2011) 43–46.
- M.H. Schwartz, J.P. Trost, R.A. Wewey, Measurement and management of errors in quantitative gait data, *Gait Posture* 20 (2) (2004) 196–203.
- G.E. Gorton 3rd, D.A. Hebert, M.E. Gannotti, Assessment of the kinematic variability among 12 motion analysis laboratories, *Gait Posture* 29 (3) (2009) 398–402.
- M.C. Carson, M.E. Harrington, N. Thompson, J.J. O'Connor, T.N. Theologis, Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis, *J. Biomech.* 34 (10) (2001) 1299–1307.
- T.E. Hewett, B. Roewer, K. Ford, G. Myer, Multicenter trial of motion analysis for injury risk prediction: lessons learned from prospective longitudinal large cohort combined biomechanical - epidemiological studies, *Braz. J. Phys. Ther.* 19 (5) (2015) 398–409.
- B.P. Boden, G.S. Dean, J.A. Feagin Jr., W.E. Garrett Jr., Mechanisms of anterior cruciate ligament injury, *Orthopedics* 23 (6) (2000) 573–578.
- T.F. Besier, D.G. Lloyd, J.L. Cochrane, T.R. Ackland, External loading of the knee joint during running and cutting maneuvers, *Med. Sci. Sports Exerc.* 33 (7) (2001) 1168–1175.
- M. Finley, J.A. Jelinek, G. Misamore, Three-dimensional analysis versus goniometric measurement of total active elevation in normal subjects, *J. Shoulder Elbow Surg.* 24 (9) (2015) 1391–1396.
- M. Banky, R.A. Clark, B.F. Mentiplay, J.H. Olver, M.B. Kahn, G. Williams, Toward accurate clinical spasticity assessment: validation of movement speed and joint angle Assessments using smartphones and camera tracking, *Arch. Phys. Med. Rehabil.* 100 (8) (2019) 1482–1491.

- [34] P.C. Charlton, B.F. Mentiplay, Y.H. Pua, R.A. Clark, Reliability and concurrent validity of a Smartphone, bubble inclinometer and motion analysis system for measurement of hip joint range of motion, *J. Sci. Med. Sport* 18 (3) (2015) 262–267.
- [35] L.T. Staheli, M. Corbett, C. Wyss, H. King, Lower-extremity rotational problems in children. Normal values to guide management, *J. Bone Joint Surg. Am.* 67 (1) (1985) 39–47.
- [36] Bafor A, Omota B, Ogbemudia A. Correlation between Clinical Tibiofemoral Angle and Body Mass index in normal Nigerian Children 2011. 1247-1253 p.
- [37] S.J. Shultz, A.D. Nguyen, R.J. Schmitz, Differences in lower extremity anatomical and postural characteristics in males and females between maturation groups, *J. Orthop. Sports Phys. Ther.* 38 (3) (2008) 137–149.
- [38] T.K. Koo, M.Y. Li, A guideline of selecting and reporting intraclass correlation coefficients for reliability research, *J. Chiropr. Med.* 15 (2) (2016) 155–163.
- [39] T.E. Hewett, G.D. Myer, The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury, *Exerc. Sport Sci. Rev.* 39 (4) (2011) 161–166.
- [40] E. Kristianslund, O. Faul, R. Bahr, G. Myklebust, T. Krosshaug, Sidestep cutting technique and knee abduction loading: implications for ACL prevention exercises, *Br. J. Sports Med.* 48 (9) (2014) 779.
- [41] M. Alam, A.M. Bull, R. Thomas, A.A. Amis, A clinical device for measuring internal-external rotational laxity of the knee, *Am. J. Sports Med.* 41 (1) (2013) 87–94.
- [42] P.O. Almquist, C. Ekdahl, P.-E. Isberg, T. Fridén, Knee rotation in healthy individuals related to age and gender, *J. Orthop. Res.* 31 (1) (2013) 23–28.
- [43] O.E. Olsen, G. Myklebust, L. Engebretsen, R. Bahr, Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis, *Am. J. Sports Med.* 32 (4) (2004) 1002–1012.
- [44] Y.K. Oh, D.B. Lipps, J.A. Ashton-Miller, E.M. Wojtys, What strains the anterior cruciate ligament during a pivot landing? *Am. J. Sports Med.* 40 (3) (2012) 574–583.
- [45] T. Ishida, M. Yamanaka, N. Takeda, Y. Aoki, Knee rotation associated with dynamic knee valgus and toe direction, *Knee* 21 (2) (2014) 563–566.
- [46] P.A. Jones, L.C. Herrington, P. Graham-Smith, Technique determinants of knee abduction moments during pivoting in female soccer players, *Clin. Biomech. Bristol, Avon* 31 (2016) 107–112.
- [47] P.S.P. Teng, P.W. Kong, K.F. Leong, Effects of foot rotation positions on knee valgus during single-leg drop landing: implications for ACL injury risk reduction, *Knee* 24 (3) (2017) 547–554.
- [48] A.A. Tran, C. Gatewood, A.H. Harris, J.A. Thompson, J.L. Drago, The effect of foot landing position on biomechanical risk factors associated with anterior cruciate ligament injury, *J. Exp. Orthop.* 3 (1) (2016) 13.
- [49] A. Gatt, N. Chockalingam, Clinical assessment of ankle joint dorsiflexion: a review of measurement techniques, *J. Am. Podiatr. Med. Assoc.* 101 (1) (2011) 59–69.
- [50] P.J. Kim, R. Peace, J. Mieras, T. Thoms, D. Freeman, J. Page, Interrater and intrarater reliability in the measurement of ankle joint dorsiflexion is independent of examiner experience and technique used, *J. Am. Podiatr. Med. Assoc.* 101 (5) (2011) 407–414.