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Reliability and Validity of the Kinect V2 for the assessment of lower extremity rehabilitation exercises

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Highlights

- Kinect V2 can reliably assess simple lower limb exercises, like the squat
- Reliability decreases with increasing complexity of the lower limb movement task
- Especially small movement amplitudes result in poor reliability
- Restricted validity for hip and knee angles and positions during some exercises
- An application in the field of early orthopedic rehabilitation is so far limited

Abstract:

Background: Besides its initial use as a video gaming system the Kinect might also be suitable to capture human movements in the clinical context. However, the system's reliability and validity to capture rehabilitation exercises is unclear.

Research question: The purpose of this study was to evaluate the test-retest reliability of lower extremity kinematics during squat, hip abduction and lunge exercises captured by the Kinect and to evaluate the agreement to a reference 3D camera-based motion system.

Methods: Twenty-one healthy individuals performed five repetitions of each lower limb exercise on two different days. Movements were simultaneously assessed by the Kinect and the reference 3D motion system. Joint angles and positions of the lower limb were calculated for sagittal and frontal plane. For the inter-session reliability and the agreement between the two systems standard error of measurement (SEM), bias with limits of agreement (LoA) and Pearson Correlation Coefficient (r) were calculated.

Results: Parameters indicated varying reliability for the assessed joint angles and positions and decreasing reliability with increasing task complexity. Across all exercises, measurement deviations were shown especially for small movement amplitudes. Variability was acceptable for joint angles and positions during the squat, partially acceptable during the hip abduction and predominately inacceptable during the lunge. The agreement between systems was characterized by systematic errors. Overestimations by the Kinect were apparent for hip flexion during the squat and hip abduction/adduction during the hip abduction exercise as well as for the knee positions during the lunge. Knee and hip flexion during hip abduction and lunge were underestimated by the Kinect.

Significance: Hence, the Kinect system can reliably assess lower limb joint angles and positions during simple exercises. The validity of the system is however restricted. An application in the field of early orthopedic rehabilitation without further development of post-processing techniques seems so far limited.

Keywords: reproducibility, agreement, markerless motion capture system, telerehabilitation

1. Introduction

Conventional 3D motion analysis systems consisting of multiple infrared cameras, reflective or illuminated markers and data analysis software are widely used to assess kinematics of body segments and the according joints. The field of application is broad and includes rehabilitation research, injury prevention and performance enhancement [1–3]. However, the acquisition of the system is expensive, data assessment and analysis time consuming and requires trained staff. Additionally, motion capturing is restricted to a laboratory environment. Marker-less motion capture systems like the Microsoft Kinect technology might offer a portable, low cost and easy to operate system for applications outside the laboratory. Besides its initial use as a video gaming system, new possibilities for the application in the clinical context were discussed to assist rehabilitation and the evaluation of therapy process [4]. First investigations on the feasibility and effect of interactive systems for the enhancement of functional parameters in clinical populations were promising. Research in motor rehabilitation using the Kinect could show improvements regarding balance and postural control as well as in upper limb range of motion and function but was mainly focused on patients with neurological disorders [5,6]. With the possibility of quantitative measurements of motor performance and real-time feedback the application of those systems might as well improve the rehabilitation process for musculoskeletal disorders after surgery [7]. The assessment and the direct control of the movement via real-time feedback could support performance quality and thereby adequate joint loading. Previous research evaluated the accuracy of the Kinect system in comparison to motion capture systems obtaining different results depending on the chosen landmark and the performed movement. For movements of the upper extremity acceptable agreements with moderate to excellent correlations were revealed [8–11]. Measurements of the trunk were assessed in functional movement tests. Good accuracy assuming valid capturing of kinematic strategies could be shown [12–14]. Lower limb landmarks were assessed in several studies for the purpose of gait analysis. Except for the hip good to excellent agreement were obtained for body landmarks and their resulting spatiotemporal gait parameters [15]. However, investigations assessing joint angles of lower limb tasks are rather sparse and contradicting. Some studies report good to excellent agreement and acceptable errors for lower limb kinematics whereas others indicate poor to no agreement and substantial errors between the systems [8,9,16–19]. The accuracy of the Kinect system seems thereby greatly influenced by the assessed joint, movement plane and lower limb task.

Therefore, it was the aim of the present study to (1) evaluate the test-retest reliability of lower extremity kinematics assessed with the Microsoft Kinect during a squat, hip abduction and lunge exercise and (2) to evaluate the agreement of lower extremity kinematics between the Kinect system and a reference 3D camera-based motion analysis system.

2. Method

Participants

Twenty-one healthy and pain free participants (13 females, 8 males; age: 40±14years; height: 172±8cm; weight: 72±15kg) without any acute musculoskeletal complains or acute infections were included in the study. Each participant received an oral and written explanation of the purpose and the study design. Prior to enrolment all participants signed a written consent form. Study approval was received by the ethics committee of the University of Potsdam where the study was conducted.

Instrumentation and Procedure

The study was conducted in a test-retest design with measurement sessions being separated by a mean of 7 days. Lower extremity movements were simultaneously assessed by the reference motion capture system consisting of 14 infra-red cameras (Vicon, Oxford, UK, MX3) and the Microsoft Kinect system (Microsoft, Redmond, USA, Kinect V2) consisting of one red, green, blue camera and a 3D depth sensor. In preparation of the measurement 16 reflective markers were placed on the participant's skin according to the lower limb "Plug-In Gait" model [20]. The Kinect camera was placed 2,5m in front of the participant and was elevated by 0.85m for an optimal field of view [21,22]. Movements were collected with a sampling frequency of 500Hz for the Vicon system and with 30Hz for the Kinect system.

Exercises were selected in regard to their frequent use in therapy of lower limb pathologies and consisted of squats, hip abductions and lunges [23,24]. All movements were performed in line of sight to the Kinect camera. Followed by familiarization trails for each movement participants were asked to perform five consecutive repetitions for each of the movements. The starting position of all three exercises was composed of an upright posture, a hip wide stance and arms extended at the side with palms facing forward. Squatting was performed with aligned knees up to 90° knee and hip flexion. Hip abduction was performed with slightly bended knees, while the leg was abducted to the side, the trunk was kept upright and the legs were kept in neutral position. For lunges the participant stepped forward with one leg and flexed both knees up to 90°. Straight leg alignment and upright trunk posture should be maintained during the execution. After each repetition, participants returned to the starting position.

Data analysis and statistical testing

The Kinect data were processed by the Microsoft Kinect Software Development Kit (SDK). Fifteen landmarks were automatically detected including bilateral shoulder, elbow, hand, hip, knee and foot as well as head, neck and torso. Hip and knee angles were defined by vector conventions (hip angles: shoulder-hip and hip-knee; knee joint: hip-knee and knee-foot). Kinematics of the lower limb including landmarks and joint angles assessed with Vicon were obtained by the "Plug-In Gait" model [20]. Joint angles were calculated by the use of Euler angles (sequence X-Y-Z). The recorded data was manually synchronized by the start and end position of the movement (distinct movement cues) without any interpolation of the data. Parameters were averaged over the five movement repetitions. Hip angles were derived in sagittal (flexion/extension) and frontal plane (abduction/adduction). For the knee angles in sagittal plane (flexion/extension) as well as knee positions in relation to the ankle in sagittal and frontal plane were assessed. All angles and positions were calculated before movement initiation (baseline) and during maximum/minimum displacement. A detailed description of all angle and position measures is given in the supplementary material of Figure S7 to S9. To assess the test-retest reliability of lower limb exercises captured with the Kinect system bias with limits of agreement (bias; LoA, ±1.96*SD) and standard error of measurement (SEM; square root of mean square error term of repeated measures ANOVA) were calculated [25–28]. For the evaluation of system agreement scatter plots of Vicon and Kinect data were created and additionally Pearson Correlation Coefficient (r) was calculated to assess concurrent validity [26]. Fixed, random and proportional bias was assessed via Bland and Altman analysis and visualized by plotting differences of the systems against the mean. Proportional bias was tested and confirmed by a significant linear regression of differences on means ($p<0.05$). With a proportional bias evident regression based Bland and Altman plots were created (*mean differences:* $D= b_0 + b_1A$ *(A= true value of measurement); 95% limits of agreement:* $D \pm 1.96\surd\ \pi/2*R$ *(R= residuals SD from regression)*) [25,29–31]. The mean difference is therefore given as formula with b_1 indicating the slope and b_0 indicating the intercept of the regression line.

3. Results

Test-Retest Reliability

For the Kinect SEM was in mean 7.6° for joint angles and 2.9cm for knee positions. Bias and LoA were in mean 3.2° and 21.0° for joint angles and 1.4cm and 7.8cm for knee positions. For the Vicon system SEM was in mean 5.4° for joint angles and 1.3cm for knee positions. Bias and LoA were in mean 2.6° and 15.3° for joint angles and 0.3cm and 3.5cm for knee positions. In both systems variability increased with the complexity of the movement task (order: squat – hip abduction – lunge) manifested in lower correlations and higher measurement errors. A summary of all reliability measures for the Kinect system and the Vicon system is displayed in Table 1.

Agreement between Kinect and Vicon

For parameters assessed during the squat *r* ranged from 0.18 – 0.83 indicating significant correlations for all parameters except knee flexion at movement initiation and two knee positions (*Knee m/l – min. [cm]; Knee a/p – bas.[cm]*). Parameters of the Kinect were lower in their extent in comparison to the Vicon system. Only maximum hip flexion showed higher angles when assessed by the Kinect. Proportional bias was evident for maximum hip flexion and baseline knee position in sagittal plane. For the standing leg during the hip abduction exercise r ranged from 0.06–0.62 with significant correlations for knee and hip angles assessed in sagittal plane. For the moving leg r ranged from 0.16–0.59 with sign. correlations for maximum hip flexion and hip abduction at baseline and maximum excursion. Joint angles of the standing leg during the hip abduction showed lower values by the Kinect when assessed in the sagittal plane. However, higher hip angles were obtained from the Kinect in the frontal plane. The same pattern was derived for the moving leg during the hip abduction with an exception for maximum knee flexion with greater angles for the Kinect. Proportional bias was evident for knee flexion angles at baseline and maximum excursion as well as for maximum hip abduction of the moving leg. For the lunge exercise r ranged from 0.01-0.83 for the front leg and from 0.15-0.80 for the back leg with significant correlations for baseline and maximum knee and hip flexion. All assessed joint angles were lower for the Kinect than for the Vicon system. Knee position in anterior and posterior direction independent of front or back leg showed as well systematic bias but indicated higher values for the Kinect. Descriptive data and information regarding the agreement is given in Figure 1 and Table 2. Additionally scatter plots of Vicon and Kinect data is provided in the supplementary material of Figure S1 to S3. Bland and Altman plots depicting systematic, proportional and random deviations between the systems are as well shown in the supplementary material of Figure S4 to S6.

4. Discussion

The purpose of the present study was to evaluate the test-retest reliability of lower extremity kinematics during a squat, hip abduction and lunge assessed with the Kinect V2 and secondly to evaluate the agreement to a reference 3D camera-based motion system. The assessment of joint angles and positions with the Kinect revealed poor to good reliability. Especially movements with small motion amplitudes resulted in high SEMs as well as wide LoAs. In general, joint angles and positions assessed with the Vicon system showed less variability. SEMs were lower and LoA narrower in comparison to the Kinect system. In both systems greatest variability between the sessions were evident for the knee and hip angles in the sagittal plane assessed during the lunge. The present results are partially in line with previous studies investigating the reliability of joint angles during lower limb exercises. Studies by Schmitz et al. and Mentiplay et al. investigated inter-session reliability of joint angles during squat movements [18,19]. Good reliabilty was obtained with MDC ranging from 2.3 to 6.0° for the assessment by Schmitz et al. One reason for a better agreement between sessions of the squat performed in Schmitz's study might be the highly standardized movement performance (restricted knee flexion and controlled movement velocity). In the present study movements were not standardized to an extent where movement amplitudes would have been influenced, as the focus was lying on situations representative for in-home rehabilitation. Mentiplay's investigation resulted in SEMs between 4.38 and 7.77° for knee and hip angles in sagittal and frontal plane during a single leg squat which is comparable with the results of the present study.

In general, it is a matter of debate whether the assessment of lower limb kinematics is reliable enough to detect clinically meaningful changes. Acceptable limits of reliability should be justified by the purpose and field of investigation. McGinley et al. promote based on a systematic review that errors up to 5° of lower body kinematics are likely reasonable during locomotion [32]. However, in rehabilitation practice patient's movements are mainly evaluated by the inspection of the therapist. Pilot investigations could show that visual examinations contain errors of up to 10° which led to under- and overestimations of joint angles during a squat movement [33]. In regards of the present study, especially the assessment of peak knee and hip angles during the lunge (SEM: 12.2°-21.4°) should be seen critical in the application of orthopedic rehabilitation where certain degrees of joint motion are contraindicated. Further it should be consider that small movement amplitudes can be source of error when assessed with the Kinect system.

The agreement between the two systems was varying regarding the assessed joint and position, the movement plane and the movement task. Bland and Altman analysis were indicating high systematic and random error particularly for joint kinematics of the hip, with overestimations of hip flexion during the squat and hip abduction/adduction during movements in the frontal plane by the Kinect. During the lunge all assessed joint angles and positions detected by the Kinect were source of error with underestimations for hip and knee angles and overestimations for knee positions. Further, indication of proportional bias showed that differences between the systems increased with the magnitude of joint angles and joint positions for mainly knee and hip flexion as well as hip abduction and knee positions in sagittal plane with overall small extent but without occurrence consistency across movements. Some of the previous studies that investigated the agreement between the Kinect and a marker-based camera system in regards to lower limb exercises gained comparable results to those of the present one. Elthoukhy et al. investigated the validity of the Kinect V2 for the measurement of lower extremity jump landing and squatting kinematics. Good consistency for peak sagittal plane but not frontal plane hip and knee angles was opposed by substantial deviations in the absolute agreement with underestimations by the Kinect. Data corrections based on a regression model could considerably improve the agreement between the two systems for joint angles assessed in the sagittal plane. An investigation by Schmitz et al. revealed excellent agreement between the Kinect V2 and a marker-based camera system for hip and knee joint angles of a squat in the sagittal, frontal and transversal plane ($r>0.55$; bias<7°). Mentiplay et al. could as well confirm excellent correlations for peak hip and knee flexion during a single leg squat ($r>0.80$), but hip and knee adduction resulted in poor to moderate correlations with systematic deviations (bias>15°) and evident proportional bias in knee and hip angles assessed in the frontal plane. Authors were attributing the good validity of the Kinect to their customized processing techniques. Neither Schmitz et al. nor Mentiplay et al. used the skeleton tracker that is inherent in the Kinect SDK. Schmitz et al. calculated virtual marker trajectories for data assessed with the Kinect which were based on the configuration of the marker-based system so that the same segment coordinate systems are used in both systems. To avoid error in joint center location estimation Mentiplay et al. identified joint centers manually based on visual inspection of the depth image. The presented studies propose that increased accuracy and validity might be achieved with adapted software algorithms and adjusted data processing techniques, but the application for real-time feedback during exercises seem limited due to the extensive and complex post-capturing processes. In the present study discrepancies between systems were most noticeable for hip joint angles in all movement tasks and for all parameters assessed during the lunge. Previous studies support the finding that the signal accuracy of the Kinect depends on landmark's location and performed movement tasks, showing higher accuracy of upper body in comparison to lower body landmarks [8,9,34]. Otte et al. revealed that the signal to noise ratio (SNR) as an overall indicator for signal quality is influenced by the landmark's ROM (SNR increases with larger movements) and decreases from upper to lower body landmarks which may explain the large deviations in the assessment of the knee position in relation to the ankle during the lunge of the present study [34].

The present study comprises some limitations. Joint angles and positions were only assessed during the beginning of the movement and at maximum excursion. The assessment over the entire course of the movement would give additional insight into the validity of the Kinect V2. Even though the synchronization of the assessed movement data was done with the highest precision based on distinct movement cues, it cannot be ruled out that the manual process added further variability to the results. Additionally, it should be considered that data assessed by the Kinect SDK underwent no further pre-processing technique and was directly used for the calculation of joint angles and positions. Even though differences between the 3D reference points of the systems exist joint angles and positions are assumed to be unaffected as calculations were conducted within each coordinate system.

In conclusion, the Kinect V2 system can reliably assess lower limb joint angles and positions during simple movements. However, the reliability of the system decreases with increasing complexity of the movement and discrepancies occur in the detection of joint angles and positions with small movement amplitudes. The agreement with a marker based 3D motion capture system ranged between poor to good and was thereby dependent on the assessed joint angle and position and the performed movement. Deviations between systems were characterized by systematic over- or underestimations and proportional error for hip joint angles across lower limb exercises as well as for knee joint angles and ankle positions during lunge movements. Therefore, in early rehabilitation phases when movements are restricted in their extent to prevent adverse events, it is indispensable to consider the variability and deviations in the assessment of joint angles and landmarks. Hence, there is an indication for further development of advanced software and real-time post-processing techniques that improve the precision and validity of the Kinect V2 system. So far an application at least in the field of early orthopedic rehabilitation seems limited.

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Declarations of interest:
None.

Conflict of interest:
None declared.

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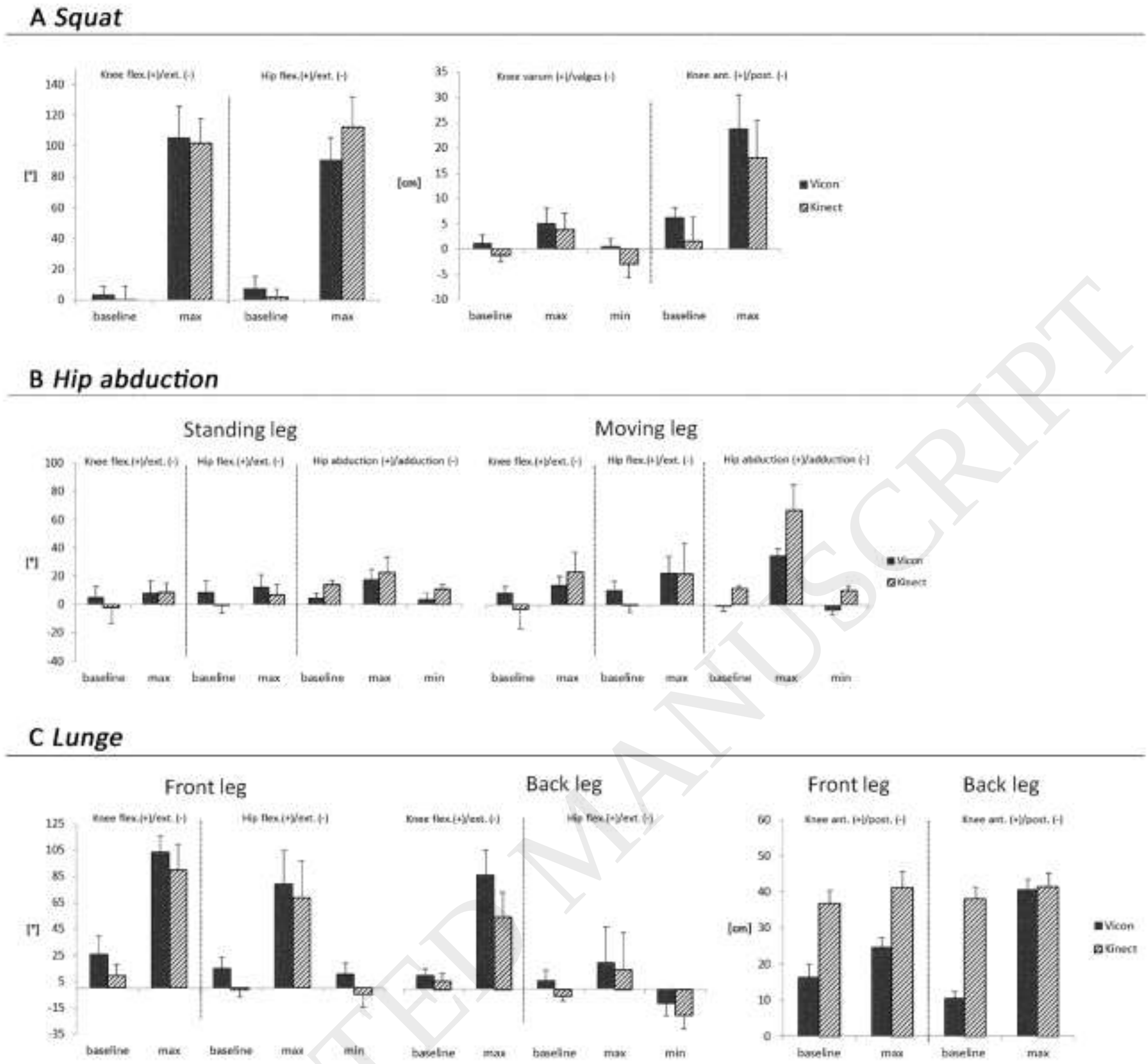

Figure 1: Descriptive data (mean±SD) of knee angles and positions as well as hip angles during the exercise of squatting (A), hip abduction (B) and lunge (C).

Table 1: Descriptive data (mean±SD) of M1 and M2 for the Kinect system and the Vicon system and according test-retest reliability for the exercises squat (only right leg assessed), hip abduction and lunge.

		Kinect		**Vicon**		**Test-Retest Reliability Kinect**			**Test-Retest Reliability Vicon**		
		M1	**M2**	**M1**	**M2**	**SEM**	**Bias**	**1.96*SD**	**SEM**	**Bias**	**1.96*SD**
Squat	Knee f/e – bas. [°]	1 ± 9	-1 ± 9	3 ± 6	4 ± 6	8.3	1.1	22.4	3.3	-1.0	8.9
	Knee f/e – max. [°]	102 ± 16	96 ± 21	105 ± 21	103 ± 18	6.8	5.9	18.4	6.4	2.3	17.3
	Hip f/e – bas. [°]	2 ± 6	7 ± 9	8 ± 8	7 ± 8	5.0	1.1	4.0	3.6	0.7	9.6
	Hip f/e – max. [°]	112 ± 20	106 ± 27	91 ± 15	88 ± 15	10.3	5.7	27.9	5.9	3.1	15.8
	Knee m/l – bas.[cm]	-1 ± 1	-2 ± 1	1 ± 2	1 ± 2	0.7	0.5	1.9	0.9	0.7	2.4
	Knee m/l – max. [cm]	4 ± 3	4 ± 3	5 ± 3	5 ± 3	2.0	0.2	5.3	1.1	0.0	3.0
	Knee m/l – min. [cm]	-3 ± 2	-4 ± 3	1 ± 2	0 ± 2	2.7	0.4	7.3	1.0	0.5	2.6
	Knee a/p – bas.[cm]	1 ± 5	-1 ± 5	6 ± 2	6 ± 2	4.8	2.6	13.0	1.1	0.0	2.9
	Knee a/p – max. [cm]	18 ± 8	16 ± 6	24 ± 7	24 ± 5	3.0	1.7	8.0	1.9	0.2	5.1
Hip abduction	*Standing Leg:*										
	Knee f/e – bas. [°]	-3 ± 12	-7 ± 15	5 ± 8	8 ± 7	12.6	5.4	34.0	5.3	-2.8	14.0
	Knee f/e – max. [°]	8 ± 6	8 ± 10	9 ± 9	12 ± 8	6.7	1.2	18.2	5.4	-3.1	14.7
	Hip f/e – bas. [°]	-1 ± 6	-1 ± 5	9 ± 8	8 ± 6	3.5	0.5	9.4	5.1	1.5	10.5
	Hip f/e – max. [°]	7 ± 6	7 ± 7	13 ± 8	11 ± 7	3.4	-0.1	9.3	4.3	2.1	11.6
	Hip abd/add – bas. [°]	14 ± 3	15 ± 3	4 ± 4	4 ± 4	2.3	-0.4	6.3	2.6	0.1	7.0
	Hip abd/add – max. [°]	23 ± 11	21 ± 3	18 ± 7	17 ± 6	8.2	2.5	22.0	4.8	1.3	12.8
	Hip abd/add – min. [°]	11 ± 3	12 ± 4	4 ± 4	4 ± 4	3.1	-0.5	8.5	3.3	0.0	7.2
	Moving Leg:										
	Knee f/e – bas. [°]	-4 ± 14	-13 ± 11	9 ± 5	7 ± 5	7.4	9.2	19.8	3.5	1.6	7.0
	Knee f/e – max. [°]	23 ± 14	19 ± 11	14 ± 7	12 ± 7	9.0	3.2	24.3	4.4	1.8	12.8
	Hip f/e – bas. [°]	-1 ± 5	-1 ± 4	11 ± 6	10 ± 6	2.8	0.9	7.5	3.0	1.4	9.2
	Hip f/e – max. [°]	24 ± 22	24 ± 28	24 ± 11	22 ± 11	11.8	-1.3	31.7	4.2	2.1	11.8
	Hip abd/add – bas. [°]	11 ± 3	12 ± 3	-1 ± 3	0 ± 4	2.1	-0.3	5.6	2.0	-0.5	10.4
	Hip abd/add – max. [°]	66 ± 19	69 ± 13	35 ± 5	36 ± 6	12.7	-2.9	34.4	3.3	-1.0	7.9
	Hip abd/add – min. [°]	10 ± 3	9 ± 4	-4 ± 3	-3 ± 4	2.7	0.9	7.2	2.1	-0.6	11.5
Lunge	*Front Leg:*										
	Knee f/e – bas. [°]	10 ± 8	11 ± 10	27 ± 14	32 ± 12	5.6	-1.1	15.2	9.0	-5.9	24.2
	Knee f/e – max. [°]	90 ± 20	95 ± 20	102 ± 12	107 ± 10	21.4	-4.7	57.8	7.3	-5.2	19.6
	Hip f/e – bas. [°]	-2 ± 5	-1 ± 6	17 ± 8	17 ± 7	3.4	-0.2	9.1	4.2	-0.3	11.4
	Hip f/e – max. [°]	68 ± 29	79 ± 14	80 ± 27	85 ± 9	20.8	-10.8	56.2	19.5	-4.9	52.6
	Hip f/e – min. [°]	-5 ± 10	-2 ± 6	12 ± 8	11 ± 7	6.1	-2.2	16.5	3.9	1.3	10.6
	Knee a/p – bas.[cm]	37 ± 4	38 ± 4	17 ± 4	17 ± 4	3.3	-1.2	9.0	1.8	-0.8	4.9
	Knee a/p – max. [cm]	41 ± 5	45 ± 4	24 ± 3	25 ± 4	3.2	-3.9	8.7	1.8	-0.3	4.9
	Back Leg:										
	Knee f/e – bas. [°]	6 ± 6	3 ± 5	11 ± 5	9 ± 7	4.9	2.6	13.2	4.1	1.3	11.1
	Knee f/e – max. [°]	54 ± 18	44 ± 11	84 ± 19	77 ± 20	12.2	9.4	33.1	11.0	6.8	29.5
	Hip f/e – bas. [°]	-5 ± 4	-6 ± 4	7 ± 7	4 ± 6	2.2	0.8	6.1	3.3	3.2	8.8
	Hip f/e – max. [°]	15 ± 28	4 ± 9	21 ± 28	8 ± 7	18.5	10.7	50.0	17.7	13.0	47.7
	Hip f/e – min. [°]	-19 ± 11	-23 ± 7	-10 ± 9	-14 ± 5	7.1	4.1	19.1	4.7	3.8	12.8
	Knee a/p – bas. [cm]	38 ± 4	39 ± 4	11 ± 2	10 ± 2	3.1	-0.5	8.5	1.2	0.2	3.3
	Knee a/p – max. [cm]	41 ± 4	43 ± 4	41 ± 3	40 ± 3	3.1	-1.8	8.4	1.0	0.3	2.7

Abbreviations; f/e: flexion/extension, m/l: medial/lateral, a/p: anterior/posterior, ab/ad: abduction/adduction, bas: baseline (initiation of movement), max/min: value at maximum/minimum excursion of movement

Table 2: Mean ± SD of Vicon and Kinect and according agreement between both systems of data assessed at M1.

	Kinect & Vicon	Agreement Kinect – Vicon			
	Mean	***r***	**SEM**	**Bias**	**1.96*SD**
Knee f/e – bas. [°]	2 ± 6	0.18	6.7	-2.6	18.0
Knee f/e – max. [°]	104 ± 18	0.88[a]	7.0	-3.7	19.0
Hip f/e – bas. [°]	5 ± 6	0.58[a]	4.5	-5.8[b]	12.3
Hip f/e – max. [°]	102 ± 16	0.81[a]	8.5	0.35x – 14.69[b,c]	0.35x ± 28.65
Knee m/l – bas.[cm]	0 ± 1	0.61[a]	1.0	-2.4[b]	2.5
Knee m/l – max. [cm]	4 ± 3	0.72[a]	1.8	-1.3[b]	4.8
Knee m/l – min. [cm]	-1 ± 1	0.27	2.3	-3.6[b]	6.2
Knee a/p – bas.[cm]	4 ± 3	0.23	3.5	1.23x – 9.58[b,c]	1.23x ±11.73
Knee a/p – max. [cm]	21 ± 7	0.83[a]	3.0	-5.8[b]	8.1
Standing Leg:					
Knee f/e – bas. [°]	1 ± 9	0.61[a]	6.6	-7.3[b]	17.7
Knee f/e – max. [°]	8 ± 6	0.47[a]	5.6	0.6	15.1
Hip f/e – bas. [°]	5 ± 6	0.63[a]	4.6	-9.4[b]	12.3
Hip f/e – max. [°]	10 ± 6	0.62[a]	5.2	-5.8[b]	14.1
Hip ab/ad – bas. [°]	9 ± 3	0.29	3.0	9.8[b]	8.1
Hip ab/ad – max. [°]	20 ± 6	0.06	9.3	5.2	25.2
Hip ab/ad – min. [°]	7 ± 3	0.11	4.0	6.8[b]	10.8
Moving Leg:					
Knee f/e – bas. [°]	2 ± 8	0.24	9.5	1.52x – 14.95[b,c]	1.52x ±33.81
Knee f/e – max. [°]	18 ± 8	0.16	10.4	1.32x – 11.83[b,c]	1.23x ± 36.52
Hip f/e – bas. [°]	5 ± 4	0.47	4.3	-11.2[b]	11.6
Hip f/e – max. [°]	23 ± 14	0.53[a]	13.0	-0.90x + 20.87[c]	-0.90x ±45.48
Hip ab/ad – bas. [°]	5 ± 3	0.59[a]	2.0	12.3[b]	5.3
Hip ab/ad – max. [°]	51 ± 11	0.56[a]	11.7	1.34x – 34.83[b,c]	1.34x ±40.36
Hip ab/ad – min. [°]	3 ± 3	0.46	2.3	13.7[b]	6.2
Front Leg:					
Knee f/e – bas. [°]	18 ± 10	0.35	9.4	0.71x – 4.40[b,c]	0.71x ± 32.90
Knee f/e – max. [°]	95 ± 14	0.58[a]	11.7	0.67x – 78.34[b,c]	0.67x ± 42.40
Hip f/e – bas. [°]	8 ± 5	0.30	6.0	-17.0[b]	16.2
Hip f/e – max. [°]	73 ± 28	0.83[a]	11.4	-10.9[b]	30.7
Hip f/e – min. [°]	3 ± 7	0.20	8.1	-15.8[b]	21.9
Knee a/p – bas.[cm]	27 ± 2	0.03	3.4	20.7[b]	9.3
Knee a/p – max. [cm]	33 ± 3	0.01	3.6	16.9[b]	9.8
Back Leg:					
Knee f/e – bas. [°]	8 ± 4	0.15	4.9	-4.2[b]	13.3
Knee f/e – max. [°]	69 ± 18	0.76[a]	8.9	-30.0[b]	24.2
Hip f/e – bas. [°]	1 ± 5	0.67[a]	4.1	0.78x – 10.30[b,c]	0.78x ± 14.13
Hip f/e – max. [°]	21 ± 28	0.80[a]	12.3	-5.3	33.1
Hip f/e – min. [°]	-13 ± 8	0.36	8.1	-7.9[b]	21.9
Knee a/p – bas. [cm]	24 ± 2	0.18	2.5	0.92x + 4.91[b,c]	0.92x ± 8.81
Knee a/p – max. [cm]	41 ± 3	0.32	2.8	0.9	7.5

Abbreviations; f/e: flexion/extension, m/l: medial/lateral, a/p: anterior/posterior, ab/ad: abduction/adduction, bas: baseline (initiation of movement), max/min: value at maximum/minimum excursion of movement, [a]: sign. Pearson Correlation Coefficient, [b]: fixed bias (sign. paired t-test), [c]: indicates proportional bias (sign. linear regression of differences and mean, regression based mean differences and 95% limits of agreement), sign. level set to α=0.05.