Bone length calibration can significantly improve the measurement accuracy of knee flexion angle when using a marker-less system to capture the motion of countermovement jump

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Abstract— **Marker-less motion capture systems can provide online recordings of human biomechanics during rapid dynamic exercises such as countermovement jump (CMJ) which could indicate an athlete's risk of injury to the anterior cruciate ligament (ACL). However, without additional post-processing the localisation accuracy of the joints can be insufficient. Subsequently, biomechanics measurements, e.g. knee flexion angles, can be severely corrupted. We propose a calibration algorithm to correct for deviations in the bone length during CMJ as recorded by a low cost marker-less motion capture system (i.e. Kinect, version 2). Results were compared to gold standard VICON measurements. In this single subject study of three CMJs the accuracy of the measured knee flexion angle during stabilisation (post jump) was significantly improved from -9.6° to -3.8° ($p<0.05$) for the left knee, and from -5.0° to 1.7° ($p<0.05$) for the right knee. In conclusion, bone-length calibration and correction may enhance the joint localisation accuracy for low cost marker-less motion capture to the extend where clinically-relevant decisions can be facilitated.**

I. INTRODUCTION

Injury to the anterior cruciate ligament (ACL) is one of the most severe career debilitating injuries that can cause long-term absence from sport and can lead to osteoarthritis in later years. Noncontact ACL injuries account for 70% to 84% of all ACL tears in both female and male athletes [1]–[3] and have been shown to occur after initial contact in landing or cutting maneuvers with the knee at full extension [4]. The ACL is one of three cruciate ligaments within the knee and it serves to stabilise this joint, preventing excessive translation of the tibia relative to the femur [5]. Pre-screening has been suggested to determine anatomical and biomechanical parameters that put athletes at an increased risk of ACL injury [6]–[8]. Risk factors for ACL injury occurrence include dynamic restabilisation on jump landing and coordinative dynamics during the eccentric loading jump phases. Equally asymmetries between knee and hip mechanics during jump movement indicate risk of ACL injury [9]. However, measuring knee, and hip joint function discretely, or indeed measuring performance outcome (jump height or force production) in isolation, fails to provide quantitative indicators on these essential precursors to injury (i.e. kinetic chain coordination and asymmetry [9]). Appropriate pre-screening procedures could determine the parameters that put athletes at an increased risk of ACL injury.

In order to quantify and analyse the factors that contribute to ACL injury risk, expensive equipment such as 3D motion capture systems have been utilised to provide quantitative biomechanical measurements that link to risk of injury in professional athletes [10]. The current gold standard motion capture system for joint localisation during dynamic movements is the VICON system (Vicon Motion Systems Ltd. Oxford, UK). It is a marker-based system relying on reflective markers being placed on well-defined anatomical locations on the participant. Several clinically-based monitoring methods included the use of 3-D motion capture equipment and force plates [11]–[13].

While gold standard equipment such as VICON can be used in a clinical setting, its application as a high throughput monitoring tool for athletes is impractical. This highlights the need for the development of an accurate, low-cost, and markerless scanner that can facilitate large-scale field based screenings. The use of commercially popular motion capture systems, e.g. Microsoft Kinect™, to assess movement has been previously suggested [14]. Recent studies [15], [16] evaluated the reliability of the Kinect in capturing biomechanical measures. Bonnechère et al. compared the Kinect to a marker based system and found large deviations from the expected measurements when subjects were performing squat movement [16]. Stone et al. compared Kinect and Vicon for the screening of ACL injury risk by investigating the drop landing movement. Their results indicated that the Kinect skeletal model likely offers acceptable accuracy for use as part of a screening tool for elevated ACL injury risk; although the exact level of accuracy needed for each measure was hard to quantify and needed further investigation [15]. To date the output of Kinect is deemed to be insufficiently accurate for clinical measurements, yet sophisticated software solutions were suggested to improve the measurement accuracy in order to satisfy clinical standards [20].

The aim of this paper is to explore the accuracy and precision limits of a state-of-the-art biomechanics software package (Kitman Labs Ltd., Dublin, Ireland [17]) which refines skeletal information acquired with Kinect. This is achieved in a comparative study measuring the accuracy and

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reliability of Kitman Labs Biomechanics solution against the industry gold standard VICON during the performance of three CMJs.

II. Materials and Methods

This was a single case validation of a novel motion capture system (CAPTURE, Kitman Labs) against the industry gold standard marker-based system (VICON Motion Systems Ltd, Oxford, UK). Testing took place in the Movement Laboratory at the Royal College of Surgeons in Ireland.

A. Gold standard measurement technology - VICON

A six camera Vicon Bonito 10 system (VICON Motion Systems Ltd., Oxford, UK) sampling at 100Hz was employed as the reference motion capture system. The infra-red cameras were positioned in a circular fashion around the athlete. A total of 39 reflective markers were placed on the head, torso, upper limbs, pelvis and lower limbs of the athlete according to Vicon's Plug-in-Gait full body model. Plug-in-Gait is based on the Helen Hayes biomechanical gait model [18] and calculates joint kinematics in the sagittal, coronal and transverse planes from XYZ marker positions and from user inputted anthropometric parameters. Prior to testing, standard calibration procedures were completed using Vicon's 5-point active wand, which defined the 3D testing volume and ensured that the markers were visible to the camera system. A static capture and calibration of the athlete was subsequently performed and dynamic capture of the CMJ followed. Data were processed in Vicon Nexus 2.1. Prior to running Plug-in-Gait, marker trajectories were reconstructed and labelled and gaps were filled using Nexus's gap or spline fill. Trajectories were smoothed using a Woltring filter (MSE 20). Plug-in-Gait was then run and the C3D file was exported to Matlab/Visual 3D for processing.

B. Kitman Labs biomechanics scanning solution

Kitman Labs Ltd. provides an advanced software solution to acquire skeletal information using Kinect version 2 sensor (Kinect for Windows and Xbox One, Microsoft corporation, Redmond, WA, USA) and Software Development Kit (SDK) via its graphical user interface - CAPTURE (Kitman Labs Ltd. Dublin, Ireland) and its web application presenting the corrected data to the user - PROFILER (Kitman Labs Ltd. Dublin, Ireland). In CAPTURE the athlete is first directed to move into the initial position in front of the sensor ensuring that the full CMJ can be recorded for any athlete height. In a second step, calibration data of the limb lengths are recorded during a 1s calibration phase while the athlete is instructed to stand still in neutral stance. In a third step, the start of the CMJ acquisition is indicated on the CAPTURE screen. In a last step, the data is checked for quality measures such as loading depth, and hand position, before the data is securely transferred to the Kitman Labs server. All further handling of the data, display of results, and alerting is facilitated in PROFILER - the Kitman Labs data base and athlete management system. The raw data was processed to correct for limb length variations using the calibration information. A 3D coordinate transformation was applied to convert the joint location data from Kinect space to real world coordinate space. The normalised head height as a function of time was analysed to determine the pre and post jump phases.

C. Bone length correction

In order to refine the skeletal data obtained from Kinect to the required accuracy limits necessary for biomechanical measurements during CMJ the joint location was corrected for variations due to changes in the bone length. This algorithm was applied to each limb assuming that the hip joint was localised in its correct position. Correction was then applied first to the knee joint, and then to the ankle. A fixed and a flexible joint were defined. The flexible joint was chosen to be the knee joint for the upper leg correction, and the ankle joint for the lower leg correction, while the fixed joint was chosen to be the hip for the upper leg correction, and the corrected knee location for the lower leg correction. The length of the bone was determined from the coordinates, x,y, and z, of the joint, j, of the flexible joint (e.g. knee) and the fixed joint (e.g. hip).

The bone vector to be calibrated was then determined as:

$$\vec{b}_{uncorr} = \vec{j}_{flex,uncorr} - \vec{j}_{fixed},$$

with the length determined as the Euclidean distance between the start and end point of the uncorrected bone vector:

$$l_{uncorr} = \left\| \vec{b}_{uncorr} \right\|.$$

The calibrated bone vector was extracted during calibration (neutral stance) as:

$$\vec{b}_{calibr} = \vec{j}_{flex,calibr} - \vec{j}_{fixed,calibr},$$

with the length determined to be the Euclidian distance between the start and end point of the calibration bone vector:

$$l_{calibr} = \left\| \vec{b}_{calibr} \right\|.$$

The correction factor was defined as:

$$f_{corr} = \frac{l_{calibr}}{l_{uncorr}}.$$

The corrected joint location of the flexible joint was then computed using the following equation:

$$\vec{j}_{flex,corr} = f_{corr} \cdot \vec{b}_{uncorr} + \vec{j}_{fixed}.$$

This procedure was repeated for the lower leg and for each frame of the CMJ dataset.

D. Kinect

For the purpose of this study the Kinect camera was mounted onto a tripod adjusted to a height of 88cm and placed in 290cm distance to the center of the VICON coordinate system. The Kinect was moved slightly to the side of the center line in order to free the view for all six VICON cameras (10° of the VICON center line). No interaction of Kinect with VICON was observed.

E. Temporal synchronisation of VICON with Kinect

Temporal synchronisation was achieved by registering the normalised head height curves according to the maximum jump height. Spatial registration was achieved through use of the VICON markers displayed in the depth map of the Kinect data and by their position recorded using VICON. The VICON data was translated in width, depth, and height direction to register both coordinate systems to their origins.

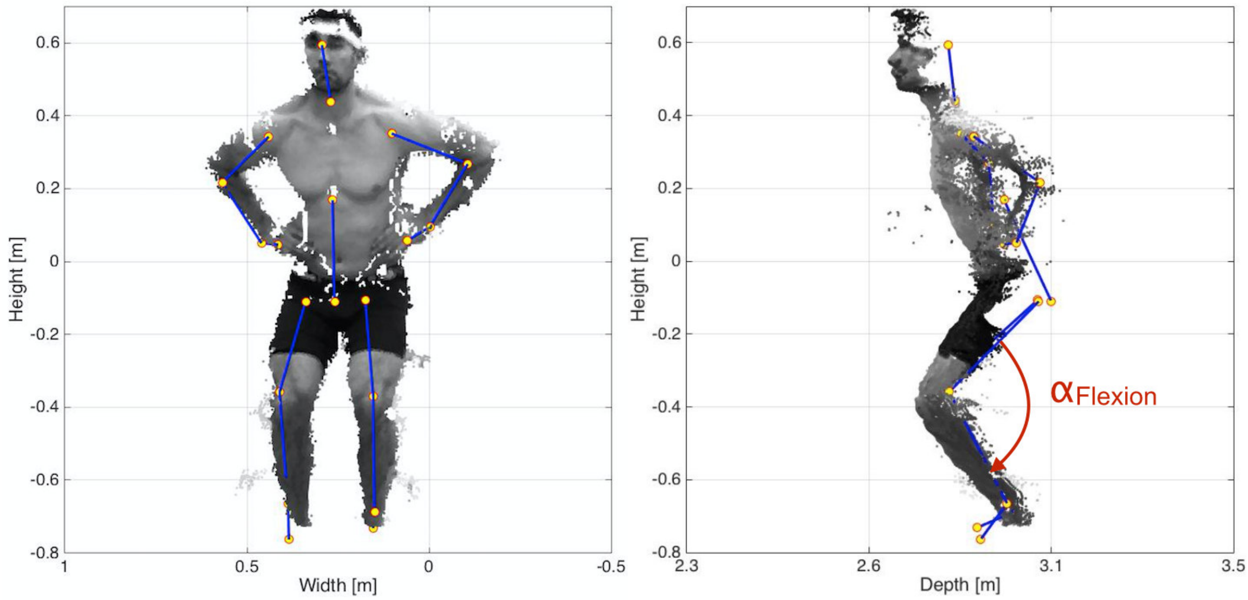

Figure 1: front (left) and side (right) view of point cloud of athlete during stabilisation period after countermovement jump. The rgb camera information was superimposed on the point cloud as grey values. The skeletal joints are indicated by yellow circles with red edges and blue bones connecting the joints.

The Kinect data was rotated in the depth and width plane by -10°.

F. Biomechanics measurements

The knee flexion angle was measured as the two dimensional angle between the upper and lower leg (as defined by the hip, knee, and ankle joint coordinates) as seen in the height and depth plane. An angle of 0° was measured for straight legs during standing. The point cloud in side and front view is displayed in Fig. 1 giving an indication of how the flexion angle measurement was taken. The knee flexion angle was measured for VICON, Kinect, and bone length corrected Kinect data. The knee flexion angle was averaged across the post-jump stabilisation period as defined by the time at which head height of half the minimum head height was achieved and passed. The results of the three jumps were used to compute the mean and standard deviation. Fig. 2 gives an indication of the flexion angle improvement due to bone length correction within the context of the gold standard test.

G. Participants

Data was obtained from a single healthy athletic male participant (age = 26years, height = 176cm, weight = 82kg). The participant had no current injury or injury history that was impeding participation in sport. In accordance with ethical procedures, informed consent was obtained. A Physical Activity Readiness Questionnaire (PAR-Q) was completed prior to task completion.

H. Test Procedure

Standardised instruction was provided to the participant and a number of familiarisation (sub maximal) jumps were completed to ensure proper technique and to account for a learning effect. A physiotherapist experienced in biomechanical analysis using Vicon placed the markers on the participant. Test-retest reliability within the laboratory has been reported previously [19].

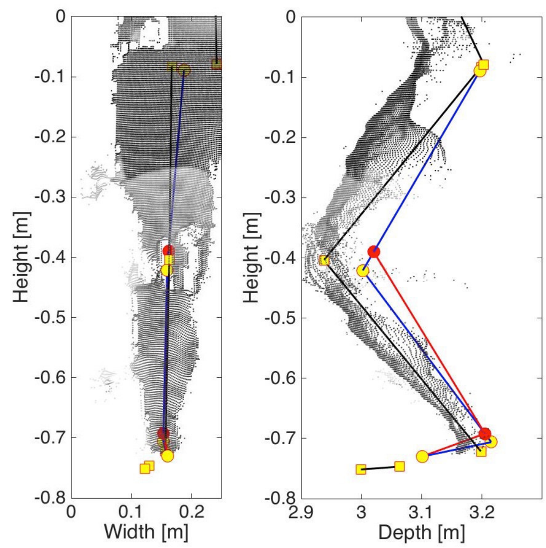

Figure 2: Front view (left) and side view (right) of right leg during stabilisation phase after CMJ. The uncorrected Kinect joints (red circles - red bones), the corrected Kinect joint locations (yellow circles - blue bones) as well as the VICON joint locations (yellow squares - black bones) visually demonstrate that bone length calibration improves the accuracy for knee flexion angle. For better orientation purposes the texture based point cloud representing the leg's surface acquired using Kinect has been superimposed in each graph.

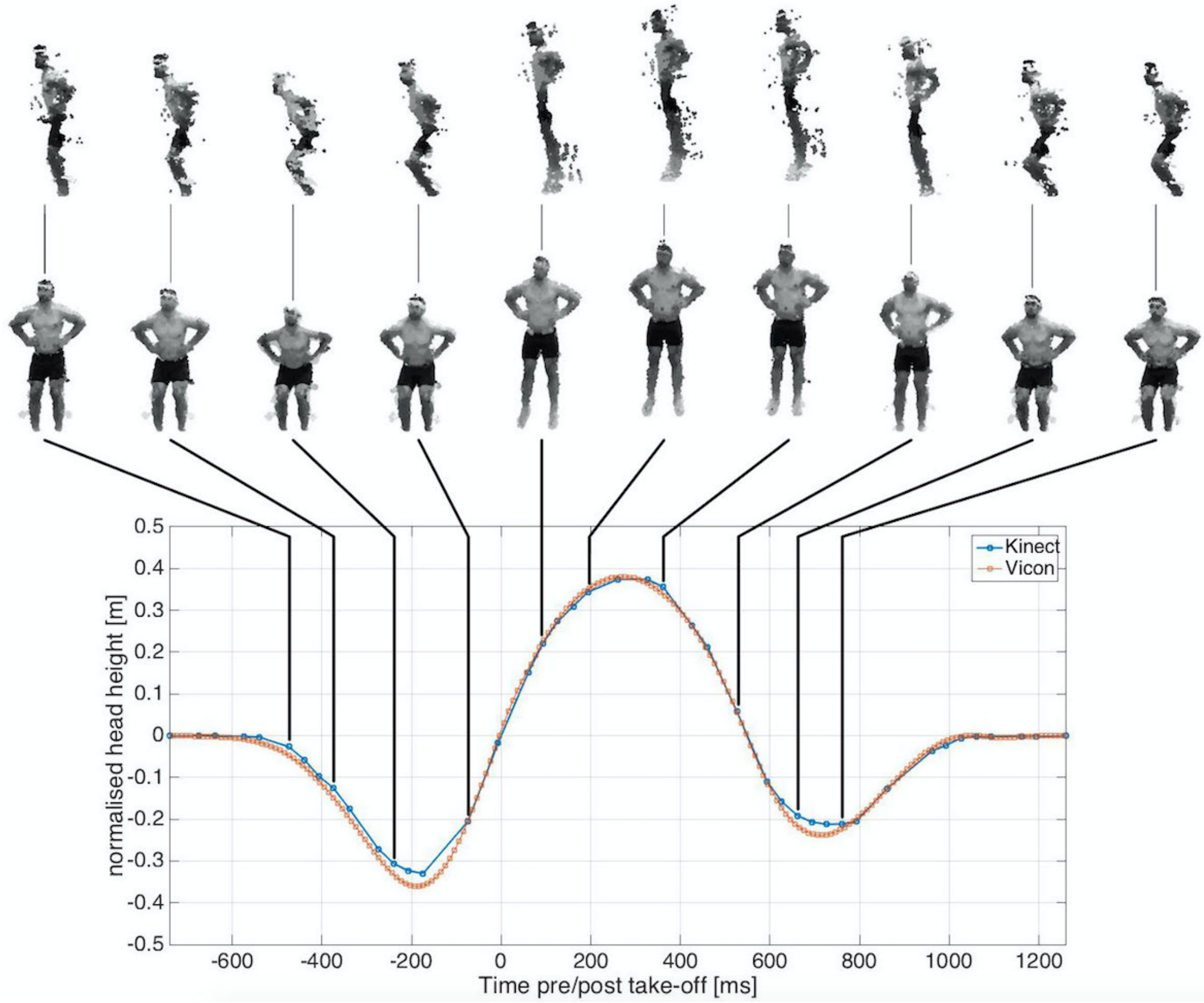

Figure 3: head displacement as a function of time pre and post take-off for CMJ as acquired using Kinect and Vicon. The texture containing point cloud acquired with Kinect is displayed at various stages of the CMJ in side view (first row) and front view (second row) above the graph.

I.Statistics

To compare whether the VICON results deviated from the results obtained for the corrected and uncorrected Kinect data a student t-test was computed. For each jump the difference between the VICON angle and the Kinect data was computed. The average across the three jumps provided the accuracy while the standard deviation of the difference provided an insight on the precision of the measurement system. The student t-test was applied to test whether the accuracy was different comparing corrected and uncorrected Kinect data. A p-value below 0.05 constituted significance.

III. Results

The effect of bone length correction on the knee joint positions can be reviewed in Fig. 2. The indication of the expected joint position (VICON - yellow squares) clearly demonstrates the improved joint location of the corrected Kinect data (yellow circles) in between the VICON knee joint and the uncorrected Kinect knee joint (red circles). This improvement has a direct and positive effect on the knee flexion angle measured.

The CMJ jump curve for Kinect in comparison to VICON is shown in Fig. 3. Above the graph the point cloud data in side and front view is presented to give an indication of the jumper's pose at each stage of the CMJ. Please note that this data was acquired with a single Kinect placed in front of the athlete. Hence, surface points of the athlete's back were occluded and not recorded.

The knee flexion results for each CMJ and the right and left side are listed in Table I. For the left knee the expected angle was measured to be 73.6° ± 4.5° while the angle output by Kinect was measured to be 64° ± 1.1° ($p=0.039$) which improved to 69.8° ± 1.6° ($p=0.157$) after correction. For the right knee the expected angle was measured to be 69.3° ± 1.5° while the angle output by Kinect was measured to be 64.3° ± 3.1° ($p=0.031$) which improved to 71° ± 4.3° ($p=0.406$) after correction.

The accuracy and precision result including the significance indicators are listed in Table II. The accuracy was improved from -9.6° ± 3.4° to -3.8° ± 3.0° ($p=0.008$) for the left knee and -5° ± 1.6° to 1.7° ± 2.8° ($p=0.012$) for the right knee.

Table I.

	LEFT / RIGHT knee flexion angle [°]		
	Kinect	*corrected Kinect*	*VICON*
CMJ 1	65.2 / 67.8	71.7 / 75.9	78.6 / 71.1
CMJ 2	62.9 / 62.6	68.9 / 69.1	69.8 / 68.6
CMJ 3	64 / 62.4	68.9 / 67.9	72.4 /68.2
mean ± std	**64 ± 1.1 / 64.3 ± 3.1**	**69 ± 1.6 / 71 ± 4.3**	**73.6 ± 4.5 / 69.3 ± 1.5**
p-value (vs. Vicon)	0.039 / 0.031	0.157 / 0.406	n.a.

Table II.

	LEFT / RIGHT knee flexion angle accuracy and precision [°]	
	Kinect	*corrected Kinect*
Difference to VICON, CMJ 1	-13.4 / -3.2	-6.9/ 4.8
Difference to VICON, CMJ 2	-6.9/ -6	0.9 / 0.4
Difference to VICON, CMJ 3	-8.4 / -5.8	-3.6 / -0.3
mean ± std	**-9.6 ± 3.4 / -5 ± 1.6**	**-3.8 ± 3.0 / 1.7 ± 2.8**
p-value (uncorr. vs. corr.)	0.008 / 0.012	

IV. DISCUSSION

Although the potential use of marker-less motion capture systems to detect variations in biomechanics values has been suggested for many years [15], [20], the accuracy of such systems during the landing phase after CMJ remains somewhat unclear. In the current study, the knee flexion angle during the stabilisation period was found to be significantly different when uncorrected Kinect data was compared to the gold-standard, while the accuracy was significantly improved through bone length calibration.

The variation in knee flexion angle for VICON across the three jumps was below 4.5° for left knee flexion and 1.5° for right knee flexion giving an insight into the intra-individual variability during CMJ. For corrected Kinect data, the accuracy was improved to -3.8° (left) and 1.7° (right). This is better than the intra-individual variation measured using VICON. The precision was 3.0°(left) and 2.8°(right) indicating excellent repeatability for this measurement in the athlete. The reduction in knee flexion error can be attributed to the thorough correction algorithms used in order to refine the raw Kinect data. Especially, the bone length correction can improve the accuracy of measuring the knee flexion angle as observed in the results of this study.

Others reported differences of up to 37° for peak knee flexion measurements during gait analysis using Kinect version 2 (day 1: 30°±3° and day 2: 31°±3°) and a 9-camera Vicon system (day 1: 67°±5° and day 2: 66°±5°) [21]. Also Pfister et al. reported large errors for Kinect version 1 in peak knee flexion during walking of up to 10° [22]. Although, acceptable error ranges for clinical biomechanics measurements are not concrete, an angular deviation between 2°–5° may be considered to be acceptable [21]. However, accuracy deficits larger than 5° indicate missing, but important kinematic information [23], [24]. Subsequently, as shown in this paper the improvement of the Kinect accuracy for knee flexion angles during CMJ enable clinical measurements when the Kitman Labs biomechanics measurement system is used.

Kinect provides a marker-less, and calibration-less system that enables full 3D capturing of the athlete's surface and inference of the skeleton while the athlete faces the camera. At least two optical cameras are necessary to facilitate stereo vision - requiring calibration in order to register the cameras in their respective location. Hence, the investigated depth sensing technology utilised by Kinect can be considered to be fast and with the appropriate software packages one may be able to measure relevant biomechanics information in real time - calibration free.

Currently available marker-based marker systems enable positioning of highly visible markers in well-known anatomical reference positions (i.e. elbow, knee, etc.). One major benefit of this technique is that the marker is always in the same position relative to the human body while markerless systems suffer from the ambiguity of capturing many more surface points on the human under investigation. Subsequently, the surface points 'seen' by the depth scanner can only be assigned to within larger anatomical reference regions (e.g. part of certain body parts). The deviation in localising a marker in the same anatomical reference position for every frame remains to be investigated. Arguably, even for marker-based motion capture systems the marker position on the skin of the athlete's surface may change its position relative to the joint. To-date, Magnetic Resonance Imaging (MRI) is the only non-invasive technique that can detect the joint and surface information with an accuracy below 4mm [25]. Yet, the physical restrictions in currently available scanners hampers proper biomechanics scanning during exercise.

Whilst the VICON system is seen as the gold standard biomechanical analysis tool, the marker placement is vital to the accuracy of the VICON and human error in marker placement combined with the movement of the markers during explosive dynamic movements is a concern to the accuracy and repeatability of the VICON [15]. These results demonstrate that low-cost markerless motion capture could provide an objective method for assessing lower limb jump and landing mechanics in an applied sports setting with good accuracy and repeatability.

Registration between VICON and Kinect was straight-forward due to the information available in how the Kinect was positioned relative to the coordinate frame of VICON. The information about the marker positions in VICON space and the visible artefacts caused by the VICON markers in the

Kinect depth images enabled an excellent mechanism to control the registration process.

Comparing marker-less to marker-based motion capture systems in simultaneous tests enables studying of the joint locations inferred from marker-less data while it also allows for developing sophisticated correction approaches. Future studies will focus on acquiring data from up to 10 volunteers at two different points in time. A larger data set will for instance enable applying machine learning approaches to correct for inaccuracies.

Although, the beneficial effect of bone length calibration was exclusively demonstrated on the example of knee flexion measurements during the stabilisation phase of CMJ, it can be assumed that this approach will have beneficial effects to correct for inaccuracies in other movements as for instance during squatting.

In conclusion, the bone length calibration that we applied in this single case study is one suggested method to improve the joint localisation accuracy for Kinect data, more advanced software solutions and validation on larger samples and populations are required to improve Kinect™ skeletal joint localisation in the future.

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