Evaluation of the Microsoft Kinect for Screening ACL Injury

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***Abstract*—A study was conducted to evaluate the use of the skeletal model generated by the Microsoft Kinect SDK in capturing four biomechanical measures during the Drop Vertical Jump test. These measures, which include: knee valgus motion from initial contact to peak flexion, frontal plane knee angle at initial contact, frontal plane knee angle at peak flexion, and knee-to-ankle separation ratio at peak flexion, have proven to be useful in screening for future knee anterior cruciate ligament (ACL) injuries among female athletes. A marker-based Vicon motion capture system was used for ground truth. Results indicate that the Kinect skeletal model likely has acceptable accuracy for use as part of a screening tool to identify elevated risk for ACL injury.**

I. Introduction

COMPARED to male athletes, female athletes who participate in high-risk sports involving cutting, jumping, and pivoting motions suffer injuries of the anterior cruciate ligament (ACL) at rates 4 to 6 times greater than male athletes [1]. It is estimated that between 20,000 and 80,000 high school female athletes suffer ACL injuries each year in the United States, and that the typical cost of health related expenses incurred as a result of an ACL injury ranges from $17,000-$25,000 [2]. Additional costs, such as the possible loss of playing time, scholarship funds, or future functional ability, are harder to quantify, but perhaps even more expensive. Although there is no single explanation for the increased rate of injury among female athletes, studies have shown that prevention programs focused on plyometrics, muscle strengthening, and improving jumping and landing technique can significantly reduce ACL injury rates [3,4].

A number of biomechanical measures about the knee, including knee abduction angle, frontal plane knee angle, and knee-to-ankle separation ratio, captured during the Drop Vertical Jump (DVJ) test have been studied as indicators of future ACL injury risk [5-7]. However, capturing these measures is not easy, as it generally involves the use of expensive equipment, such as 3D motion capture systems, in performance labs, or manual joint identification from the recordings of a calibrated camera system.

A fast, low cost, portable system for capturing these biomechanical measures would facilitate more widespread screening of female athletes for elevated risk of ACL injuries, and, thus, allow for more targeted use of injury prevention programs. With the release of the Microsoft Kinect sensor device and corresponding Software Development Kit (SDK), a low cost method for obtaining a three-dimensional skeletal model (joint positions) of an individual without the need for wearable markers or manual joint identification became available. A number of studies have looked at the accuracy of both the Kinect sensor itself, as well as the characteristics of the skeletal model, for various tasks in a variety of fields [8-11].

In [9], the Kinect was used to measure the gait parameters of walking speed, stride time, and stride length, for the purpose of in-home gait monitoring and fall risk assessment. Good agreement was found between the measurements from the Kinect and those from a Vicon motion capture system on a set of 102 walking sequences from 13 individuals. However, this work did not use the Kinect skeletal model, instead using custom algorithms to segment and track people.

In [10], a set of tests was devised and conducted to assess the performance of the Kinect skeleton for use in virtual environment control interfaces where gesture recognition is of key interest. The researchers concluded that the Kinect would likely be suitable in many gesture recognition applications, with the main limitation being the latency of the Kinect skeleton.

In [11], the author explored the potential and limitations of the Kinect as it applied to stroke rehabilitation; specifically, the ability of the Kinect skeleton to track a patient's joint locations during a physical therapy session. Although issues were encountered when multiple people were in view of the Kinect, the potential of the device was found to be very promising.

In this work, the Kinect skeletal model was evaluated for use in capturing four biomechanical measures during the DVJ task which have proven to be useful in screening for future ACL injuries [5-7]. Specifically, knee valgus motion as measured from initial contact (IC) to the point of peak flexion (PF), frontal plane knee angle at both IC and PF, and knee-to-ankle separation ratio measured at PF. A Vicon motion capture system was used for ground truth.

Section II of this paper starts with a brief description of the Microsoft Kinect and the DVJ, followed by an explanation of the biomechanical measures used in this work and how they are computed. Section III contains the results of a small study conducted for evaluation purposes, including intra-class correlations and error distributions for the Kinect as compared to the Vicon on each measure. Finally, Section IV contains a brief discussion of the results, including the implications for use of the Kinect as a screening tool for future ACL injuries.

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II. Methodology

A. Microsoft Kinect

The Microsoft Kinect sensor, shown at the top of Fig. 1, utilizes a pattern of actively emitted infrared light and an infrared sensitive camera to generate a depth image (an image in which the value of each pixel depends on the distance to what is being viewed) at 30 frames per second that is independent of visible lighting. The Microsoft Kinect SDK, a software development package that works with the device, is capable of identifying and segmenting people from this depth image and fitting a 20 point skeletal model to the bodies [12]. The skeletal model, with approximate location of each joint, is shown at the bottom of Fig. 1, while color images, with joint locations from the lower extremities overlaid, are shown in the middle of Fig. 1.

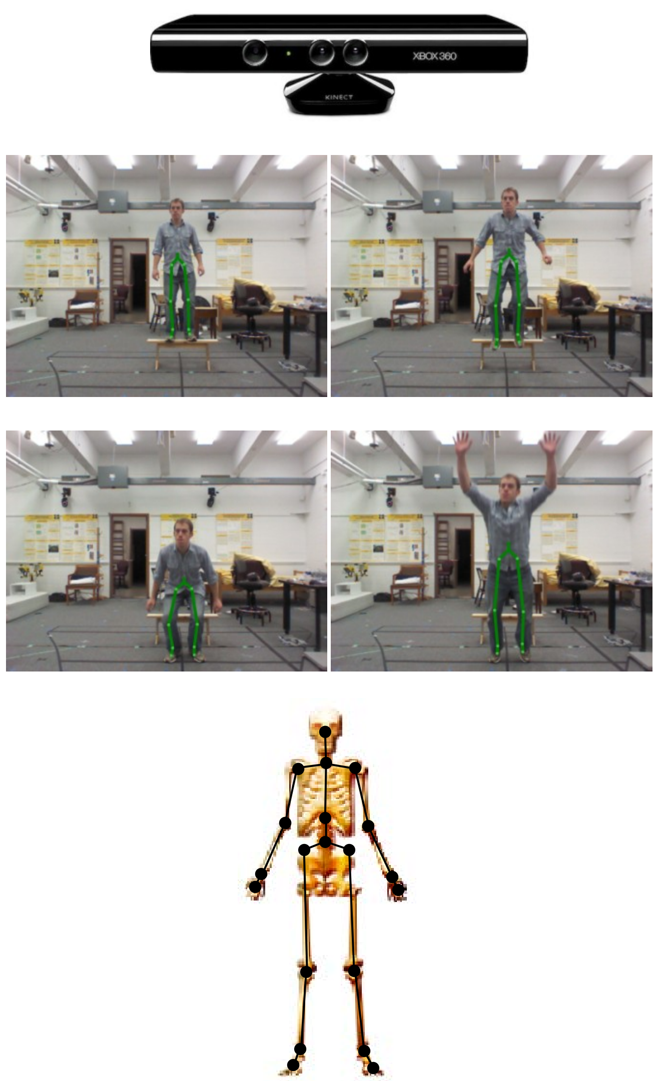


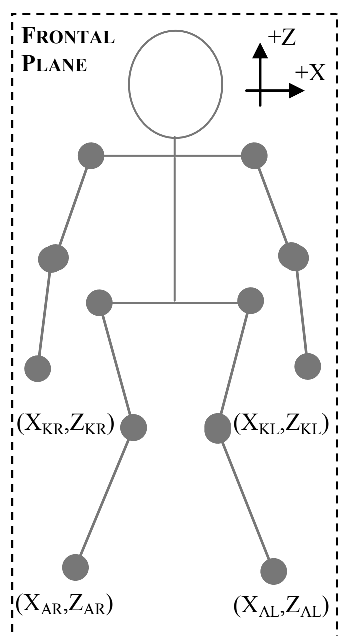
Fig.1. **Top:** Microsoft Kinect sensor. **Middle:** Skeletal model generated by the Microsoft Kinect SDK overlaid on color images captured by the Kinect during a DVJ. **Bottom:** Diagram showing the approximate location of the 20 joints making up the Kinect skeletal model.

B. Drop Vertical Jump

The Drop Vertical Jump (DVJ) test, illustrated in the middle of Fig. 1, has been established as an ideal task for evaluating the motions that put athletes at risk for ACL injuries [5]. The DVJ starts with an athlete standing on a platform approximately 30 cm high. The athlete is instructed to drop from the platform to the ground and then perform a maximal vertical jump, as if going up to get a rebound in basketball. Two specific points of interest during the DVJ are the point of initial contact (IC), when the athlete first makes contact with ground following the drop from the platform, and the point of peak flexion (PF) following IC and before leaving the ground for the vertical jump. It is at these points that the biomechanical measures of interest are typically captured.

C. Biomechanical Features

Although the Kinect joint location data is three dimensional, there is insufficient information about each body segment (bone) to measure the 3D knee abduction angles as described in [5]. Thus, all measures are preformed on the frontal plane, similar to those measured by single camera systems using manual joint identification [7].The equations for computing the biomechanical measures used in this work: knee valgus motion (KVM), frontal plane knee angle (FPKA) at IC and PF, and knee-to-ankle separation ratio (KASR), are shown in Fig. 2.



$$KVM_x = |X_{Kx}(IC) - X_{Kx}(PF)|$$
$$(abduction+, adduction\ -)$$

$$KASR = \frac{|X_{KR} - X_{KL}|}{|X_{AR} - X_{AL}|}$$

$$FPKA_x = cos^{-1}(\widehat{v_{KAx}} \cdot \widehat{v_{KGx}})$$
$$\widehat{v_{KAx}} = \frac{\langle X_{Ax}\text{-}X_{Kx}, Z_{Ax}\text{-}Z_{Kx} \rangle}{\|\langle X_{Ax}\text{-}X_{Kx}, Z_{Ax}\text{-}Z_{Kx} \rangle\|}$$
$$\widehat{v_{KGx}} = \frac{\langle 0, Z_{Ax}\text{-}Z_{Kx} \rangle}{\|\langle 0, Z_{Ax}\text{-}Z_{Kx} \rangle\|}$$

Fig.2. Illustration of the biomechanical measures used in this work: knee valgus motion (KVM), frontal plane knee angle (FPKA), knee-to-ankle separation ratio (KASR). All measures are made in 2D following projection of joints onto the frontal plane.

KVM captures the change in horizontal position of the knee joint on the frontal plane from IC to PF. FPKA captures the angle formed by a unit vector going from the knee joint to the ankle joint, and a unit vector going from the knee joint straight down. Finally, KASR captures the ratio of the horizontal distance between the knees to the horizontal distance between the ankles.

The orientation of the frontal plane (which is defined by a unit vector orthogonal to the plane) is constant for each DVJ. The unit vector defining the orientation is computed by subtracting the mean of the hip joint positions while standing on the platform from the mean of the hip joints positions immediately prior to take-off for the maximal vertical jump. The position of the plane is set such that the mean of the hip joint positions immediately prior to take-off is located on the plane. After the frontal plane has been defined for a DVJ, all of the joint positions are projected onto the plane for analysis.

III. Results

To evaluate the accuracy of the Kinect skeletal model for capturing the biomechanical measures described in Section II, 15 participants were recruited to take part in an IRB monitored human subjects study. Due to technical issues with their Vicon data, two subjects had to be removed resulting in 13 participants in the final dataset. Each participant performed between 5 and 7 DVJs, yielding a total of 84 DVJs. The age of the participants ranged from 20 to 31, and the heights ranged from 1.62 to 1.93 meters. Ten were male and three were female. All participants wore shorts or form fitting tights, such that their knee position was clear to the Kinect. For all DVJs, the platform was centered approximately 3.5 meters in front of the Kinect and the subject moved toward the Kinect during the DVJ. The results of the evaluation are shown in Table I and Fig. 3.

Locations of the hip, knee, and ankle joints were recorded from both the Kinect skeletal model and the Vicon motion capture system. The “Plug in Gait” module and standard marker set were used with the Vicon [13]. This module uses the positioning of markers on specific anatomical locations, along with measurements of a subject’s height, leg length, knee width, and ankle width, to estimate the location of the actual joints of the human body.

The point of IC was manually identified for each DVJ by observation of the Vicon toe and heel markers, as the Kinect and Vicon datasets were temporally aligned. The point of PF was determined independently for each system, as the point at which the mean of the hip joints were at their lowest height following IC, and before take-off for the maximal vertical jump. Finally, the Kinect data was preprocessed with a median filter to remove noise and a Gaussian filter to smooth the data.

The intra-class correlation coefficient (ICC) (two-way, single measure, absolute agreement) was used to assess the degree of agreement between the Kinect and Vicon on each measure. KVM had the lowest ICC value; 0.81 and 0.85 for the left and right leg respectively. The other measures had similar ICC values of approximately 0.89 for both legs.

TABLE I
DIFFERENCE BETWEEN KINECT AND VICON

	LEFT LEG		RIGHT LEG	
	ERROR (u±σ)	ICC (95% int.)	ERROR (u±σ)	ICC (95% int.)
Knee Valgus Motion (mm)	0.38±14.51	[0.72,0.87]	5.38±15.72	[0.77,0.91]
Fr. Plane Knee Angle at IC (deg)	-1.19±1.88	[0.74,0.95]	-0.77±1.69	[0.81,0.94]
Fr. Plane Knee Angle at PF (deg)	-1.84±3.21	[0.77,0.95]	-0.09±3.75	[0.85,0.93]

	ERROR (u±σ)	ICC (95% int.)
Knee-to-ankle Separation Ratio at PF	-0.06 ± 0.12	[0.84, 0.93]

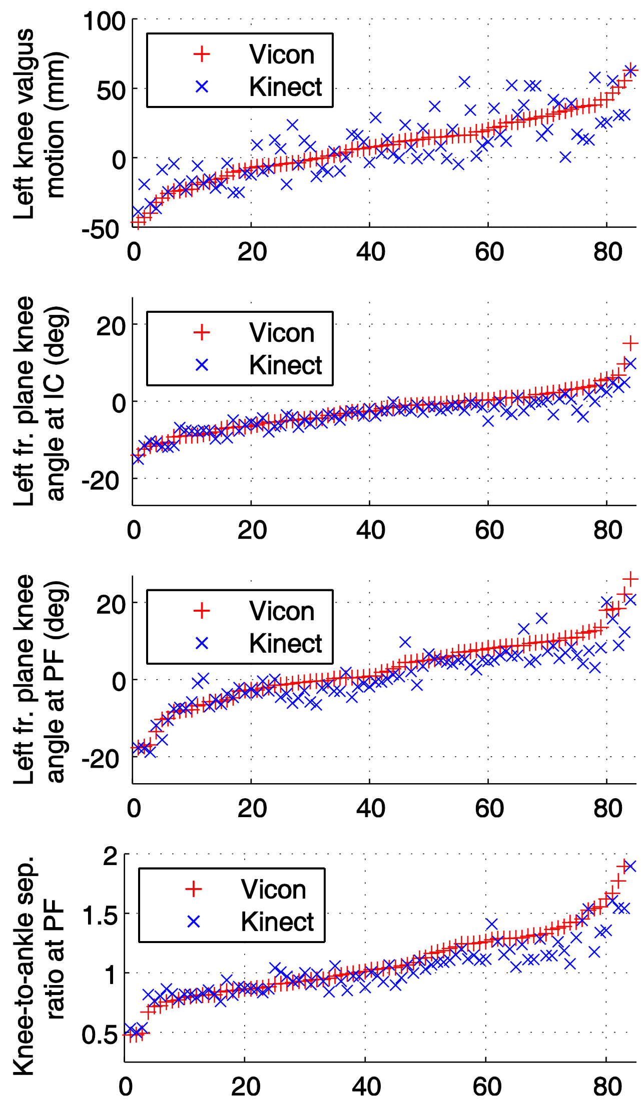


Fig.3. Graphs comparing the Kinect and Vicon systems on the four biomechanical measures evaluated in this work. For knee valgus motion, and frontal plane knee angle at IC and PF, only the left leg is shown. For each measure, the trials have been sorted in ascending order based on that measure, as captured by the Vicon motion capture system.

Standard interpretations of the ICC suggest values above 0.75 indicate excellent agreement between the measurements.

In terms of normal error distribution, FPKA at IC was slightly more consistent, based on the standard deviation, than FPKA at PF. Both measures showed little bias, with the mean of the error distributions being close to zero. Similar values were obtained for each leg, indicating no bias between legs.

The KASR at PF error distribution showed a standard deviation of 0.12. Most of this variation was due to the measurement of knee width, as oppose to the measurement of ankle width, which was more stable. The individual measures of ankle width and knee width at PF had error distributions of -16.7±36.0 mm, and 3.7±16.6 mm, respectively. Absolute error in the KASR tended to increase as KASR became larger than 1, suggesting such poses may not be captured as accurately by the Kinect skeletal model.

IV. Discussion

A number of studies have indicated that prevention programs focused on plyometrics, muscle strengthening, and improving jumping and landing technique can significantly reduce ACL injury risk. However, a fast, low cost, portable screening tool for elevated ACL injury risk is needed to significantly reduce the incidence of such injuries and the high costs associated with them. Such a screening tool would allow more widespread, targeted use of proven prevention programs among those most at risk. However, the biomechanical measures that have been associated with increased ACL injury risk are currently hard to obtain, requiring either expensive equipment or time consuming manual identification of joint locations by experts.

Based on data reported in other studies [5], the results of this study indicate 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 is hard to quantify and needs further investigation. At the least, given three repeated DVJs from a subject, FPKA at IC should be well within the accuracy needed for a basic screening instrument. It should be noted that the measurement errors were not explicitly tested for normality.

The Kinect offers many advantages over traditional systems. First, the cost of the Kinect is trivial compared to typical motion capture systems. Second, the Kinect has a key advantage over the Vicon and similar systems, in that no placement of markers is required. Marker placement on specific anatomical locations is vital to the accuracy of the Vicon. However, human error in marker placement, combined with movement of markers during large, fast motions, is often problematic. Not placing markers also saves significant time and speeds up the measurement process. Not needing to place anything on the body is also an advantage over wearable sensor based systems, along with the ability to record the skeletal data for later playback and viewing by a clinician.

The point of IC for each DVJ was manually identified from the Vicon toe and heel markers. As the Vicon and Kinect data were temporally aligned, a separate identification of IC was not made using the Kinect data. However, in an actual system, the identification of IC would need to be based on the Kinect data. This should be relatively straightforward from the foot and ankle points of the Kinect skeleton.

A rather simplistic method was used to estimate the orientation of the frontal plane and the frontal plane was assumed to be constant during each DVJ. A better method for frontal plane approximation could improve the results and will be further investigated.

Finally, the main limitations of this study include the sample size, 13 individuals, and the small number of female participants. As the system is aimed at ACL injury prevention among female athletes, the large number of male subjects included in the sample population may not be representative of the target population. Future work will include further validation of the Kinect skeletal model using a larger and more varied sample.

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