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Estimating Forces during Exercise Activity using Non-Invasive Kinect Camera

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***Abstract*—Recognizing errors that may occur during participant exercise performance and reduce the risk of exercise-related injuries is important to improving adherence in wellness management. We demonstrate the feasibility of using Kinect camera for estimating ground reaction forces during a jumping exercise, as an alternative to more expensive and traditionally used force plate platforms. The Kinect camera provides a cost-effective solution for participants in analyzing exercise performance in home-based exercises. The proposed technique, which is based on the conservation of momentum, is easy to implement and can be used to provide feedback to the participant in real-time. Our results indicate that the ground reaction forces that are estimated using the 3D joint data obtained from the Kinect camera closely match the forces obtained using a force plate.**

***Index Terms*—Kinect camera, Vicon camera, Force plate, Exercise performance.**

I. Introduction

It is well-known that over 25% of the body injuries involve ankles and knees. Such injuries generally occur because of poor jumping posture where large amounts of forces act on the feet resulting in injuries such as laceration [1], knee dislocation[2], etc. It is therefore important as a exercise practitioner to understand the jumping kinematics and help adjust the participant's jumping technique to decrease the chance of injury and increase the exercise adherence.

In the recent times, it is not uncommon that participant's perform basic exercises at home in the absence of physical trainer. In these home settings, wearable sensors are not the performers first choice as it hinders participant's motion and performance. In such scenarios, technology can play an important role in monitoring the exercise performance and provide real time feedback to the participant to minimize injury risk and improve home exercise adherence. Such technologies should be reliable in monitoring the activity and fast enough to provide real time feedback. The sensors that provide data to these software should be cost efficient and flexible to mount such that they do not hinder the participant's range of motion [3].

Quite a few studies standout from the literature that attempt to estimate these ground reaction forces during participant's performance [4], [5], [6]. In [7], authors attempt to calculate the landing forces in a simple running exercise. They claim that the body is made of seven segments and based on the running style different segments contribute to the forces acting on the feet. To estimate the forces on each segment, markers are placed on the segments and the entire activity is tracked using VP310 video recorder. This data is analyzed using an Expert Vision three-dimensional software which makes use of the basic equations of motion to estimate the segment forces. They claim that the estimated forces were within 10 % of the forces captured using force plate.

Estimating the landing forces is also important for training athletes in sports such as badminton, basketball, etc. In [8], authors attempt to calculate the landing forces from a jumping smash activity in Badminton. In this study, a game was video recorded during a competition, and analyzed using Peak Motus 2000 software. This software uses a novel mathematical model that represents the lower extremities of a human body using Newton-Euler equations. These equations act upon the video data recorded and output the forces and moments produced during the landing phase in the jumping smash activity. From the analysis the authors concluded that the athlete during the landing phase transfers the force from the landing foot to the other foot to reduce the potential injury to the landing foot.

Almost all of the above studies require analysis to be performed on recorded data. However such procedures is not suitable in providing real-time feedback while the person is performing exercise activity especially in home exercises. In this paper we present a real time algorithm based on simple kinematics equations of motion; by integrating joint data collected using a Kinect camera, we achieve a fast and cost effective solution for estimating ground reaction forces. Our technique provides near accurate results when compared to that of traditionally used Force plate readings.

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II. EXPERIMENTAL SETUP

A. Kinect

In recent years, the Microsoft Kinect Camera has been extensively used to study human motion. In [9], the performance of dancers is evaluated by comparing it against a reference standard. In [10], [11], [12], the role of the Kinect camera in rehabilitation is discussed. In [13], [14], an exercise feedback system which recognizes exercises using a classifier is discussed. The performance is compared to a reference to provide real-time guidance and feedback in a tele-rehabilitation system. In [15], the authors used the joint information to ensure anonymity of the people during surveillance. In [16], the data obtained from a Kinect camera is analyzed to estimate the anthropometry of participants.

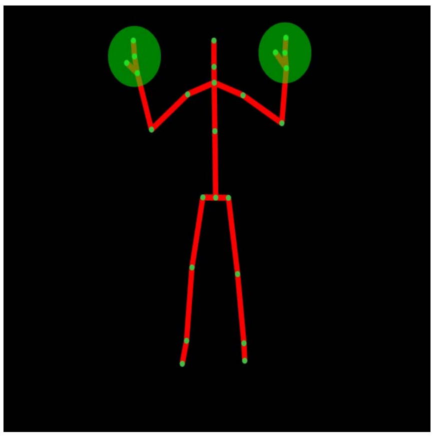


Fig. 1: Joint locations obtained from the Microsoft Kinect 2.0 cameras.

One of the novelties of the Kinect camera is to track a set of 25 joints and provide the 3D coordinates of the joints. The algorithm integrates depth information with shape information for estimation of joint positions. The time series of joint positions is provided at 30 frames per second by the algorithm. One frame of the joint positions obtained from the Kinect camera is shown in Fig. 1. The coordinate positions of the joints obtained using Kinect camera were calibrated to the real-world units and, hence, ready to use for analysis. The camera has 60° vertical field of view and 70° horizontal field of view. For precise tracking of body joints, the participant is required to stand no more than 4.5 meters from the camera.

B. Force Plates

Force plates are considered has industry standards in force measurements. In our experiment, we have used Model OR6-5-1 Force Plate manufactured by Advanced Mechanical Technology, INC. The data collected using the force plates gives us the forces and moments along all the 3-dimensional axis at a rate of 1000 samples per second.

C. Vicon Cameras

During our experimentations, we observed that the sampling rate of the Kinect camera (30 frames per sec) was too small to capture the exact motion during jumping and landing phases of the participant's performance. To validate our technique, we incorporated the Vicon motion capturing system that offers 100 frames per second sampling rate and therefore provides higher resolution of the performance. The Vicon motion capturing system is an infrared marker-tracking system that offers millimeter resolution of 3D spatial displacements. These cameras are considered as gold standard in human body motion analysis software industry [17].

D. Data Collection

In this study Kinect, Vicon and Force plates were used in parallel to track the participant's movement. Prior to data collection, an approval from Institutional Review Board(IRB) was received and the participant was required to sign a thoroughly reviewed consent form. We asked the participant to stand on the force plate to measure their weight and then asked to perform a series of vertical jumps while keeping their arms straight down so the arms would not affect the jump. The data were collected for a total of 9 jumps.

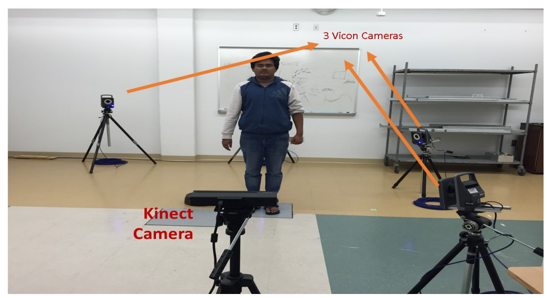


Fig. 2: Experimental Setup.

III. MOTION OF SINGLE JUMP

Figure 3 illustrates the kinematics of a single jump. This figure plots the spine base joint position from the data collected using the kinect camera. Point A is the initial start position from rest. During the time interval between 'B' to 'C', the participant squats down in preparation for jump. The interval from C to D is the take-off time during which the participant exerts force on to the force plate. The point 'D' is the exact time instance at which the maximum force is applied on the force plate and the participant takes-off into the air. The interval from D to E is the time for which the participant is in the air. Time 'E' is the exact instance at which the participant touches down on to the Force plate. During E to F the participant is in the landing phase and starts to exert force again on to the force plate. The interval from F to G is the time it takes for the participant to recoil back to the rest position.

In Fig: 4, We can observe the changes in the ground reaction forces with respect to the spine base positional data collected using the Kinect. In 4, the green line indicates the position of the spine base with respect to kinect and the blue line indicates the forces exerted on the participant. Initially when the participant starts to squats down the force decreases and

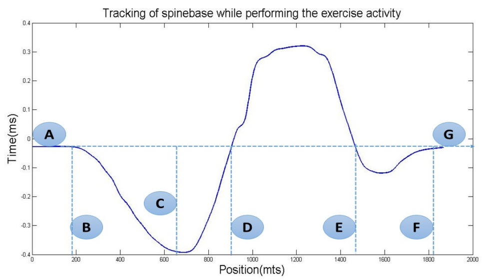


Fig. 3: Plot of spine base over a single jump.

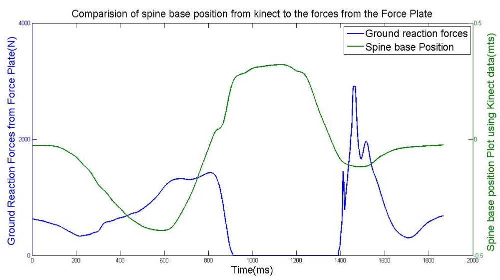


Fig. 4: Position of participant spine joint as tracked using Kinect camera during a single jump along with the forces exerted on to the Force plate. Observe the force plate data is zero while the participant is airborne and spikes up during the landing phase.

then the force gradually increases as the person starts to raise from the squatting position. The force becomes zero when the participant is in the air and the force suddenly raises to the peak when the person lands and later settles to mg which is the force exerted when the person is in stationary position.

IV. Method

A. Impulse-Momentum Approach

In this approach, we used the impulse-momentum method to calculate the ground reaction forces from the data collected using Kinect 2.0 and Vicon and compared it to that of forces captured using Force plates. Since the forces between the two objects are equal in magnitude and opposite in direction, and since the times for which these forces act are equal in magnitude, it follows that the impulses experienced by the participant and force plate are also equal in magnitude and opposite in direction. As an equation during the take-off and landing phases, this can be stated as

$$\int_{B}^{D} F_{GRF}\ dt = m \cdot v_{to} + \int_{B}^{D} m \cdot g\ dt \quad \textbf{Take-off phase} \tag{1}$$

$$\int_{E}^{F} F_{GRF}\ dt = m \cdot v_{tl} + \int_{E}^{F} m \cdot g\ dt \quad \textbf{Landing phase} \tag{2}$$

where, F_{GRF} is the ground reaction forces captured using the force plate, v_{to} is the instantaneous velocity during the Take-off phase calculated from the data collected from Kinect or Vicon, v_{tl} is the instantaneous velocity during the Landing phase calculated from the data collected from Kinect or Vicon, m is the mass of the participant, and g is the gravitational acceleration (9.8 m/sec^2).

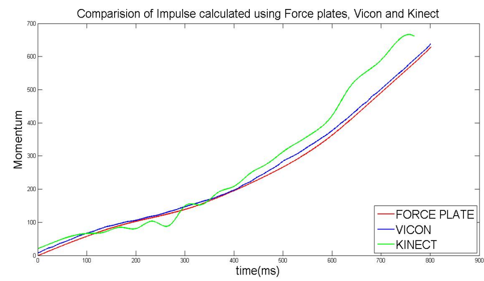


Fig. 5: Impulse calculated using force plate, vicon and kinect data. The graphs shows that the impulse calculated using force plate data is approximately equal to impulse calculated using kinect and vicon data. This shows that the change in momentum is conserved during jumping phase.

Figure 5 verifies that our data is in accordance with what is expected from equation 1. It can be observed from the figure that the impulse calculated at the force plate is approximately equal to the impulse calculated using the data collected from Kinect and Vicon.

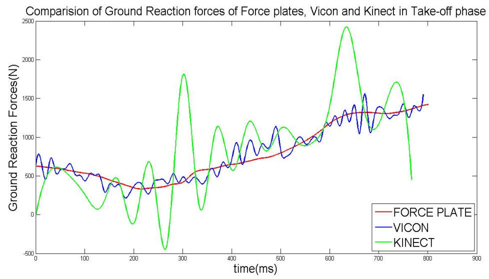
Using equations 1 and 2, we can derive an equation given in 3 for instantaneous force acting on the participant feet using just the kinect or vicon data. The computed force, can be used as an approximate value in the absence of force plate.

$$F_{GRF}(t) = m \cdot \frac{\Delta x}{\Delta t^2} + \big(m \cdot g\big) \tag{3}$$

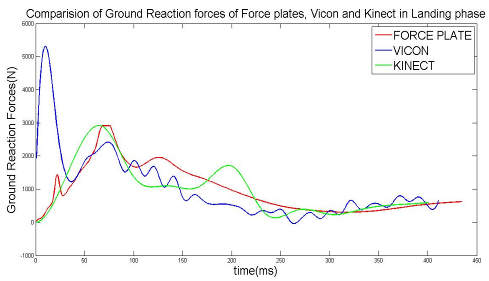
where, $F_{GRF}(t)$ is the instantaneous force acting on the participant at any given time t, Δx, is the change in spine-base position as observed in kinect or vicon camera, Δt, is the time-difference between successive frames in the kinect ($\frac{1}{30}$ sec) or vicon ($\frac{1}{100}$ sec).

In Fig. 6a, the forces exerted by the ground during the Take off phase of the jump is tracked.we observe that the forces calculated using the Kinect or Vicon data follow the Force plate curve . The participant during the take off phase squats down initially due to which the force exerted by the ground on the person decreases i.e. from frame 1 to 220 the force gradually decreases and once the person starts applying the force and raises up to take off, the forces gradually increases. It is observed that after frame 220 the force gradually increases and reaches the maximum point just before the take off.

In Fig. 6b, the forces exerted by the ground during the Landing phase of the jump is tracked. In the Landing phase, from the time the person touches the ground the forces starts to increase and reaches the maximum. Once the person starts to relax the forces gradually decreases and settles at mg when he is at stationary position. In Fig. 6b, it is observed that from frame 1 to 70 the forces gradually increases and reaches the maximum point, after frame 70 the forces gradually decreases and becomes constant when the person is in stationary position.



(a) Comparison of forces during Take off phase using Force Plate, Vicon and Kinect.



(b) Comparison of forces during landing phase using Force Plate, Vicon and Kinect.

Fig. 6: Comparision of forces calculated using equation 3 during take-off and landing phases

The errors observed during the force calculations using the data from the kinect can be accounted due to mounting of the camera, calibration procedure. Further research needs to be conducted to develop standard calibration procedures and mounting techniques to reduce the errors.

V. Conclusions

Detecting anomalies in physical activities or exercise performance remains a challenging issue to prevent injuries in athletes and beginner exercisers, performing basic exercises in the absence of expert trainer. Existing techniques require complete video recordings of the performance, in order to analyze motion and body posture errors, that may lead to injuries. Such techniques may not be applicable to provide real-time feedback to the participants and help correct exercising errors in real-time. Using basic equations of motion, we presented a formulation based on impulse-momentum method to estimate forces acting on the participant feet, that is easy to compute in real-time. We showed that the forces computed using this technique based on the 3D joint coordinates that were gathered using the non-invasive and inexpensive Kinect camera are in good agreement with that of forces captured using industry standard force plates. The results show that the accuracy of the computed forces from the joint data can be improved by calibrating the device and careful mounting. Further research may be needed, in investigating the use of multiple Kinect cameras to improve the accuracy of the estimated forces.

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