Estimation of Force during Vertical Jumps using Body Fixed Accelerometers

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***Abstract*— a method of estimating force using an accelerometer is presented. This model is based on estimating the resultant acceleration of a body at its centre of mass using a tri-axial accelerometer. A data set of ground reaction forces are gathered using a force platform, which is used as the control for this experiment. Signal processing techniques for resampling the accelerometer signals, along with a method of cross correlation to align the force platform and accelerometer traces are used. The purpose of this study was to compare force calculated using accelerometer data from the SHIMMER device, with force platform data on counter movement and drop jumps, for use in sports biomechanics. The method was validated using twelve physically active adults who performed 5 counter movement jumps and 5 drop jumps from a height of 0.30 m. An accelerometer was attached near the participant's centre of mass and simultaneous force and acceleration data were obtained for the jumps. Minimum eccentric force and peak concentric force were calculated concurrently for countermovement jumps and peak landing forces were calculated concurrently for drop jumps. The results showed moderate to low levels of agreement in forces and a consistent systematic bias between the results from the force platform and accelerometer. However, good agreement between the accelerometer and force platform was observed during the eccentric phase of the countermovement jump.**

***Keywords* – signal processing, accelerometer, force platform, vertical jumps**.

I INTRODUCTION

Vertical jumps are a very important measure in sports biomechanics research. Drop jumps (DJ) and countermovement jumps (CMJ) are routinely used to monitor levels of performance in sports training and conditioning. Techniques in sports such as basketball, volleyball athletics and gymnastics often involve variations of these jumps. Performance statistics such as peak force (PF), rate of force development (RFD), flight time (FT) and reactive strength index (RSI) are often calculated from these jumps to measure an athlete's progression over time.

The force platform is a generally accepted instrument for determining performance in DJ and CMJ[1]. It is often known as the gold standard in force measurements. While the force platform provides a good measure of the ground reaction force (GRF) acting at the foot ground interface, it is generally accepted that this represents the resultant force acting on the whole body centre of mass (CoM)[2]. Alternatively, the force acting on the CoM may be estimated by attaching accelerometer near the CoM and multiplying the measured acceleration by the body mass.

There are an increasing number of wireless sensor technologies on the market in recent years which provide tri-axial accelerometry. These wireless sensor technologies are useful in sport biomechanics applications since they provide adequate sampling rates and allow subjects to perform normal movements with little encumbrances. There is also the added benefit of performing the exercise in an ecologically valid environment rather than in a laboratory [3, 4].

A recent study estimated the energy expenditure of elite athletes using tri-axial accelerometers[5]. The raw data was post-processed. The processing load was reduced by using lower sampling rates and less computationally intensive filters, allowing the operating microprocessor frequency to be reduced. A reduction in current draw was consequently seen, lowering the overall power of the device. Similarly, another study realised and validated a new low-cost measurement system using a tri-axial accelerometer to perform movement functional analysis in sports environments[6]. A similar study compared flight times by analysing the acceleration and GRF signals, showing good correlation[6]. Another study showed a comparison of the accelerometer and force platform measures during jumping and found moderate levels of agreement between devices when measuring vertical peak force[7]. Similarly, vertical forces were examined in squats and found moderate to high correlations between forces from an accelerometer and force platform[8]. By contrast, very good agreement between devices was found in determining flight times[1] in vertical jumps[9].

There is limited data that supports the use of the accelerometry as an acceptable alternative to force platform for evaluating CoM forces during jumping and to date, no studies have compared the SHIMMER[10] device with force platform. Therefore the aim of this work was to evaluate the SHIMMER device accelerometer estimates of CoM force against more generally accepted force platform, while reducing the processing load by having less computationally intensive functions in the post-processing phase.

II METHODS

a) Test Protocol

Twelve volunteers, 6 females (age 25 ±2 years, height 1.71 ±0.06 m, mass 68.18 ±6.18 kg; mean ±SD) and 6 males (age 22.67 ±3.5 years, height 1.78 ±0.05 m, mass 74.43 ±6.45 kg; mean ±SD), who were injury free at the time of testing, participated in the study. Ethical approval was granted by the local University Research Ethics Committee and all participants completed an informed consent form before testing. All participants were familiar with CMJ and DJ. Participants' height and mass was measured. The height of the CoM was estimated as 57% of total height for males, and 55% for females[11]. This is equivalent to just below the waist at the navel on all participants[12]. The SHIMMER accelerometer was attached to each participant at this point.

Participants performed a standardised warm up consisting of 3 minutes of running at a self-selected, comfortable pace followed by two sets of ten dynamic stretches (forward and sideways hip swings, bodyweight squats, lunges) and submaximal attempts at double leg and single leg drop jumps. After the standardised warm up, subjects performed 5 CMJs and 5 DJs from a 0.30 m height. A rest interval of 30 seconds was used between trials of the same jumps type and 3 minutes between jump types to avoid residual effects of fatigue on performance[13]. The CMJs involved the subject standing on the force platform then squatting down to self-selected position and jumping up, making sure to land back down on the force platform. The participants' hands were placed on their hips at all times throughout the jump, and there was no tucking motion in the air. The aim of the jump was to minimise contact time while also attempting to achieve maximal height[14]. Similar instructions were given when performing the DJ, keeping in mind to drop from the box rather than to jump off the box[14].

b) Hardware

Jumps were performed on dual AMTI OR6-5 force platform[15]. An accelerometer from the SHIMMER platform was attached to participants near their CoM. Figure 1 shows the drop jump set-up beside the dual force platforms and the SHIMMER device in the SHIMMER docking station.

Figure 1: Drop Jump Test Set up

c) Data Measurements

All signal processing was performed offline using custom MATLAB code. The SHIMMER device has the functionality to log the data to a Micro SD card. Data is saved in a binary file of type 'uint8', which means that each number is an unsigned, positive integer of 8 bits in length. Prior to testing, the device was calibrated. The calibration parameters are used to convert raw analog-to-digital convertor (ADC) values to SI units, i.e. m/s^2 for accelerometer data. Figure 2 displays the accelerometer coordinate system used during calibration. The calibration parameters are stored in a file on the Micro SD card. This file is read by the SHIMMER firmware and the appropriate parameters are then stored in the configuration header during data logging.

The configuration header is the first 136 bytes of the file. Within the configuration header the sensors on the device to be enabled are set to a '1' in the relative bit of the first 10 bytes. The sensor configuration is also set up in this header, such as the sampling frequency and range of each device. The accelerometer calibration values and the

[1] The length of time the participant is in the air between initial contact time before the jump and contact on the landing

gyroscope calibration values are stored the configuration header.

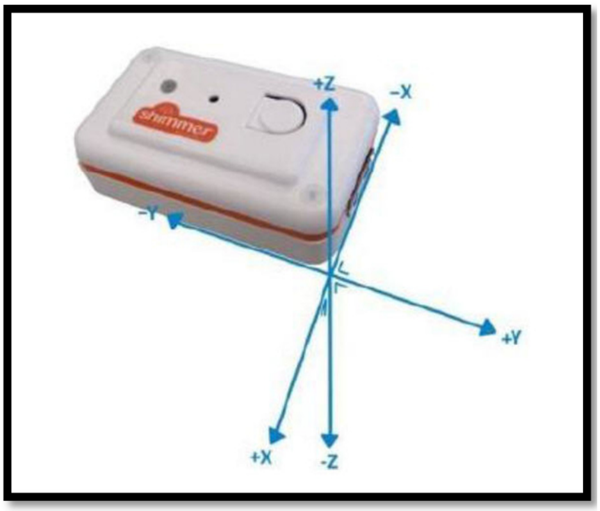

Figure 2: Accelerometer Coordinate System

The calibration parameters are used to convert values output by the on-board ADC into their standard units. The tri-axial accelerometer output, y_a, is given by:

$$\hat{y}_a = (K_a \cdot R_a \cdot \hat{a}) + \hat{b}_a \tag{1}$$

This can be rearranged in terms of the acceleration, $\hat{a}$, by:

$$\hat{a} = R_a^{-1} \cdot K_a^{-1} \cdot (\hat{y}_a - \hat{b}_a) \tag{2}$$

Where, $\hat{y}_a$, is the uncalibrated accelerometer output vector, $\hat{a}_a$,is the acceleration vector of the sensor unit, $\hat{b}_a$,is the accelerometer offset bias vector, K_a is the sensitivity matrix for the accelerometer, R_a, is the alignment matrix for the accelerometer, all shown by equations 3 – 7 respectively:

$$\hat{y}_a = \begin{bmatrix} y_{a,x} \\ y_{a,y} \\ y_{a,z} \end{bmatrix} \tag{3}$$

$$\hat{a}_a = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \tag{4}$$

$$\hat{b} = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} \tag{5}$$

$$K_a = \begin{bmatrix} K_{a.x} & 0 & 0 \\ 0 & K_{a,y} & 0 \\ 0 & 0 & K_{a,z} \end{bmatrix} \tag{6}$$

$$R_a = \begin{bmatrix} r_{a.xx} & r_{a,xy} & r_{ax,z} \\ r_{a,yx} & r_{a,yy} & r_{a,yz} \\ r_{a,zx} & r_{a,zy} & r_{a,zz} \end{bmatrix} \tag{7}$$

d) Data Analysis

The SHIMMER device firmware requires the sampling frequency to be a factor of 1024 Hz (the max sampling frequency), i.e. the sampling period must be an integer multiple of 1/1024 s. A function was created in MATLAB using sinc interpolation to resample the accelerometer signal at 1 kHz. Synchronization between the force platform and accelerometer was then achieved by setting the sampling rate of each device to 1 kHz and matching the events of the peak force/ acceleration on landing. These were easily identified from the force and accelerometer data sets.

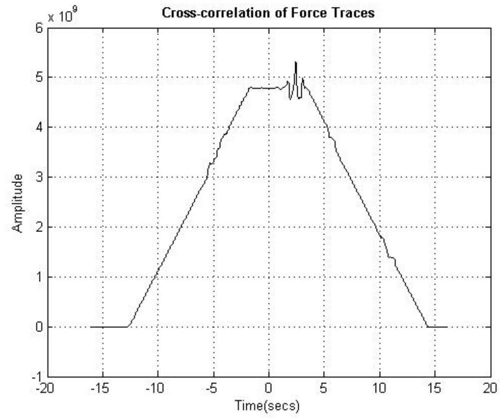

Figure 3: Cross Correlation of the Force Platform and Accelerometer Traces

Measuring the similarity of the force trace and the accelerometer trace, by means of a cross correlation function in MATLAB, allowed both signals to be aligned (Figure 3). The two signals are input into the cross correlation function for analysis, the signals can be of two different lengths, but must have the same sample rate. The function identifies the peaks in the signals and calculates the length of time one signal is lagging the other. This value is then used to realign the signals by removing unnecessary data from the beginning of the leading signal. An example of the synchronized traces from the force platform and accelerometer respectively can be seen in Figure 4.

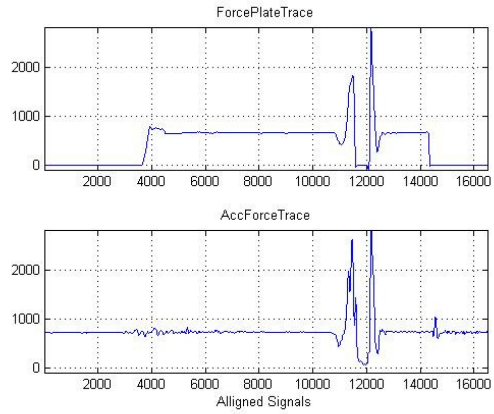

Figure 4: Aligned Force Platform and Accelerometer Trace

A 4th order Butterworth filter with a cut-off of 10 Hz was applied to smooth the accelerometer signals and the force platform traces[16]. A cut off frequency of 10 Hz was shown to be the best cut off frequency when analysing accelerometer data[17].

The resultant acceleration (a_R) was calculated using the acceleration from the X, Y and Z axis in the following formula:

$$a_R = \sqrt{{a_X}^2 + {a_Y}^2 + {a_Z}^2} \quad (8)$$

This resultant acceleration was then multiplied by the mass of the subject to give the resultant force (F_{AR}) from the accelerometer:

$$F_{AR} = m \times a_R \quad (9)$$

For the force platform, the resultant Force (F_{FPR}) was calculated using the force from the X (F_{FPX}), Y (F_{FPY}) and Z (F_{FPZ}) axis in the following formula:

$$F_{FPR} = \sqrt{(F_{FPX})^2 + (F_{FPY})^2 + (F_{FPZ})^2} \quad (10)$$

The best trial for each type of jump was selected for analysis. These trials were identified from the flight time of the jump based on the force platform data. The corresponding accelerometer trace was then analysed alongside the force platform trace. The minimum eccentric force and the peak concentric force were the dependent variables calculated for the CMJ. The dependent variables calculated for the DJ were the Peak Forces (PF) on take-off and landing.

e) Statistical Analysis

All data was analysed statistically using SPSS for Windows software. Force platform and accelerometer data sets were compared using Bland-Altman plots[18] and interclass correlation coefficients (ICCs) with 95% Confidence Intervals (CI)[19]. Means were compared using Student t-tests with alpha set at 0.05. Relative reliability was also investigated for both instruments using ICC with 95% CI.

III RESULTS

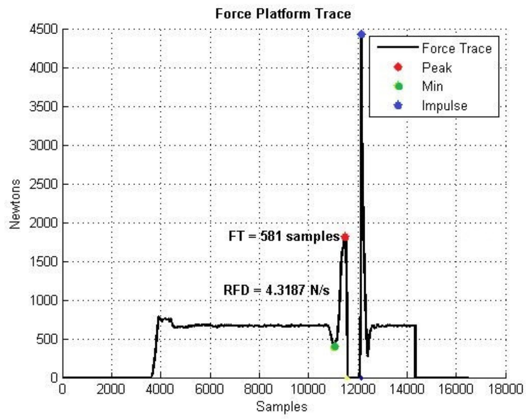

Figure 5: Counter Movement Jump Force Trace

One of the CMJ force traces from the force platform data set can be seen above in Figure 5. The minimum eccentric force, peak concentric force and impulse on landing can be seen clearly in this plot. The forces calculated here were used to calculate the rate of force development before take-off. The flight time was also calculated whereby a flight phase began when the force dropped below 10 N and the landing phase began when the force advanced above 10 N. The flight time was used to decide which trial was the best jump from each participant, to be used in the results.

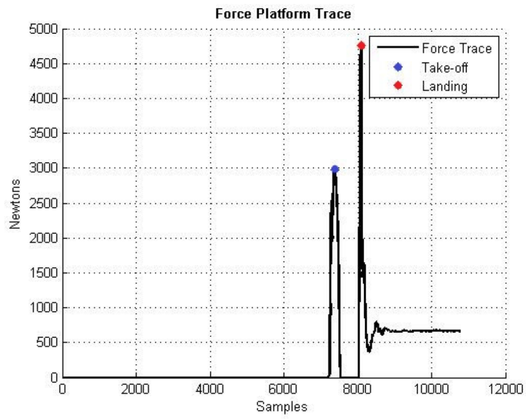

Figure 6: Drop Jump Force Trace

Similarly one of the DJ force traces from the force platform can be seen in Figure 6. The peak impulse on initial and final landing can be identified in this plot. The flight time was calculated similar to above to identify the best trial to be selected per participant.

Table 1 shows the mean results (±SD) for all variables for CMJ. The minimum eccentric force returned an ICC of 0.936; however the peak concentric force returned an ICC of much lower at 0.602. A significant systematic bias was observed between force platform and accelerometer measures (Table 1). The greatest percentage difference between methods was found for the peak concentric force with a 35.8% difference found for CMJ.

The mean results (±SD) for all variables for DJ are shown in Table 2. The Initial PF returned an ICC of 0.768, while the final PF ICC was much lower at 0.404. The percentage difference between methods was very large for both PFs in the DJ with differences of 30.9% and 53.6% respectively.

Examples of the correlation between the accelerometer and force platform using Bland-Altman plots can be seen in Figure 7 and Figure 8. Figure 7 shows the Minimum Eccentric Force during CMJs and Figure 8 shows the peak force during DJs.

Table 1: Comparison of Force Plate and Accelerometer for Counter Movement Jumps

	Min. Eccentric Force	***Peak Concentric Force***
Force Plate ±SD (N)	239 ±162	1727 ±359.52*
Accelerometer ±SD (N)	228 ±133	2346 ±746.33
% Difference	4.8	35.8
Systematic Bias (N)	11	-619
ICC (95% CI)	0.936 (0.780 – 0.982)	0.602 (-0.268 – 0.889)

*Denotes p<0.001

Table 2: Comparison of Force Plate and Accelerometer for Drop Jumps

	Peak Force Take-off	***Peak Force Landing***
Force Plate ±SD (N)	3378 ±1077*	2521 ± 714*
Accelerometer ±SD (N)	4422 ± 1185	3872 ± 586
% Difference	31.9	53.6
Systematic Bias (N)	-1044	-1351
ICC (95% CI)	0.768 (-0.193 – 0.950)	0.404 (-0.89 – 0.813)

*Denotes p<0.001

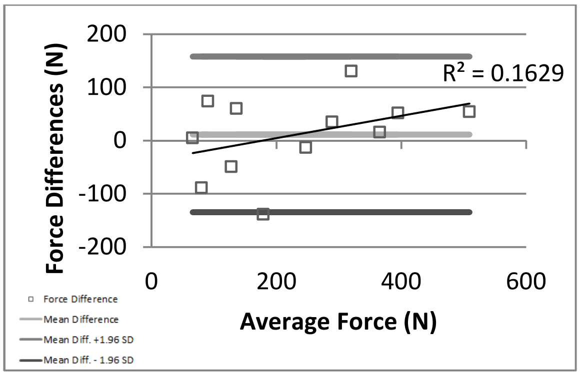

Figure 7: Bland-Altman Plot of Minimum Eccentric Force during CMJs

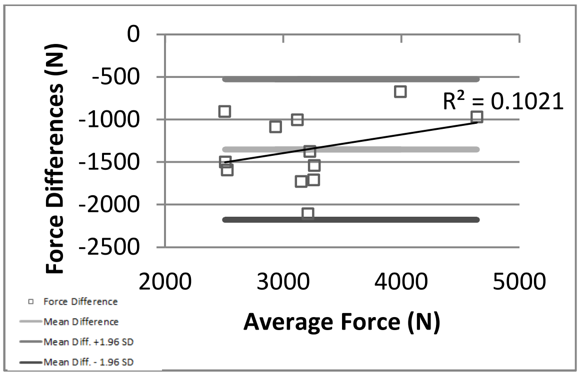

Figure 8: Bland-Altman plot of Peak Force during DJs

IV DISCUSSION

The results of this investigation generally showed significantly higher estimations in peak forces for resultant accelerometer data compared to the resultant force platform data in both the CMJs and DJs. For CMJs the results showed good agreement between the accelerometer and force platform for minimum force in the eccentric phase of the jump. The ICCs and limits of agreement were low to moderate for peak concentric force in the CMJ and peak forces at take-off and landing in the DJ. These differences can be attributed to the fact that resultant accelerometer data was compared to resultant force platform data, rather than the vertical component of the devices. This is due to the fact that when the subject begins the jump they lean forward and the orientation of the accelerometer changes. Correcting the force components of the accelerometer arising from axis orientation shifts presents technical challenges when using accelerometry that are avoided when using the fixed axis set up of a ground mounted force platform. This change in orientation of the accelerometer can be measured by utilizing the gyroscope functionality in the SHIMMER device, which would accurately denote which axis of the device was registering the vertical acceleration and allow correct recalculation of forces relative to the inertial axis. Thus by utilizing the gyroscope data in the analysis of the acceleration and transferring the vertical components from the X and Z planes to the

Y plane, the actual vertical component of the jump can be measured and compared with the vertical component (Z) of the force platform. The apparent over-estimation of the accelerometer compared with the force platform may also be caused by high frequency vibrations of the device that occur during rapid movements and changes of direction. Despite low pass filtering some of these high frequency accelerations remain, causing higher calculated peak forces from the accelerometer.

V CONCLUSION

Due to the fact that only the resultant acceleration and force was analysed, a consistent systematic difference exists between devices. This study identified that the acceleration measured using the SHIMMER device cannot be used interchangeably with the force calculated using the force platform. However further research is required on the use of the SHIMMER device with the added functionality of the gyroscope to analyse the results more accurately and achieve the vertical component only of the acceleration of the body. Work has begun on using the data from the gyroscope to identify vertical components of the accelerometer data sets.

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