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Motion Capture System versus Common Force Platform Methodologies for Vertical Jump Analysis

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Abstract

Background: This study compared vertical jump phase identification using a three-dimensional motion capture system to three common force platform based methodologies.

Methods: Thirty-two semi-professional male rugby league players (23.3 ± 4.1 years) volunteered to participate in the study. Participants completed six vertical jumps on a force plate with landmark body markers for the motion capture system analysis. The data from the motion capture system was then analysed against three common methods used in vertical jump analysis.

Results: Eccentric phase time, concentric phase time, time to peak force and rate of force development for method one were significantly different ($p<0.001$) from motion capture system data. Method 2 was significantly different ($p<0.05$) for eccentric phase time identification compared to motion capture analysis. No significant differences were found among the three groups for maximum concentric force when compared with motion capture system data.

Conclusion: While no differences were found in the maximum force values, differences were found in the eccentric and concentric phase times. The accurate identification of the start and ending of the phases is essential to correctly measure the time to peak force and rate of force development during the vertical jump. The rate of force development and time to peak force has been identified as key predictors of sports performance and therefore care must be taken in the methods chosen to measure these important variables.

Keywords: Athletic performance; Sports; Movement; Reproducibility of results; Eccentric phase; Concentric phase; Vertical jump; Rate of force development

Introduction

The vertical jump (VJ) is commonly used to assess both athletic ability and to monitor the effectiveness of training programs for elite athletes. The VJ is also used by health care professionals to measure muscle function in the elderly [1], monitor injury rehabilitation [2] and assess other clinical conditions [3-5]. Designed originally by Dudley Sargent in 1921 as "the physical test of a man" [6], VJ height is assessed as the difference between standing height and the jump height. While the Sargent method of calculating jump height is still used regularly today, more recently modern technology has provided additional devices such as force platforms to determine VJ performance. Force platforms offer not just the calculation of jump height but a number of other key determinates of athletic performance such as the rate of force development (RFD) and time to peak force (TPF) [7].

However despite the wide spread use of force platforms in determining VJ performance, questions remain on the accuracy and reliability on VJ variables calculated from force platform data [8,9]. The poor reliability of key VJ based force-time variables appears linked to a number of factors. The type of VJ (counter movement jump or squat jump, arm swing or no arm swing, etc.), the participants used (athletic versus non-athletic) and in particular the methods used to identify the eccentric and concentric phases of the VJ. The methods used to identify these phases of the VJ are crucial in the accurate and reliable extraction of meaningful force-time variables such as RFD and TPF [8,9-16].

The archetypal VJ involves a clear eccentric (descent) and concentric (ascent) phase of the subjects center of mass [8]. Participants began in a still standing position with hands on their hips and when instructed to do so drop into a squat position and instantly project their jump vertically attempting to achieve the highest possible jump height. However, presently no consensus exists on the commencement of the VJ and consequently without a definitive start point the calculation of a number of variables is difficult to determine [8]. Furthermore a recent report found significant differences in force platform data when using three different methods of force calculations [17]. The absence of a robust and consistent method for identifying the key movement phases of a VJ will continue to impact on the quality of research in this area. As a result of the inconsistencies in methodologies, RFD and TPF variables have been found to be unreliable [18,19] and so their use in athletic monitoring must be questioned.

A recent literature review and meta-analysis [8] demonstrated that there are three commonly used methods for phase identification from force platform data in the analysis of VJ. Using a neutral pool of VJ data significant differences were found among the three methods for the identification of the eccentric and concentric phases, which subsequently influenced key performance variables TPF and RFD. The authors concluded the results demonstrated a clear need for a robust method when identifying the phases from force platform data during the VJ. Therefore the purpose of this study was to compare how VJ phase identification using a three-dimensional motion capture system differs from three common force platform based methodologies.

Methods

Participants

The experimental approach to this study was a well-designed control study without randomization. Thirty-two semi-professional rugby league players volunteered to participate in the study (height 176.5 ± 14.3 cm, weight 87.0 ± 15.7 kg). This population group was chosen to ensure they were familiar with VJ performance testing. The players had participated in rugby league for 13.3 ± 3.3 years and regularly performed 3-5 training sessions per week and 1 game per week during the playing season. Following the completion of a medical history questionnaire all participants were deemed healthy and free from any cardiovascular or neuromuscular irregularities. Prior to participation, the experimental procedures and potential risks were explained to the participants and all provided written informed consent. Data was collected following preseason training but before match-play to minimise the effect of injuries from the game and maximize training status. The study was approved by the University of the Sunshine Coast Ethics Committee in accordance with the Declaration of Helsinki.

Testing procedures

Participants attended the Sport Science Laboratory on 2 separate occasions to participate in a familiarization session and a testing session. The test session consisted of a warm-up that included a series of cycle ergometry and dynamic range of movement activities before subjects randomly completed 6 VJs on a force platform. During the VJ, subjects used the stretch shortening cycle and incorporated 6 jumps without arms as per methodology adopted by Street et al. [20]. Vertical ground reaction force (Fz) data were sampled with multicomponent force plate (Bertec, Columbus, Ohio, USA) at 1000 Hz, and the duration of the data collection period was 5 seconds. Force platform data were processed using Visual3D computer software (Visual3D, C-Motion, Inc. Maryland, USA) with the data then analysed using the three methods identified as the common methods of interpretation [8]. These methods were then compared with the position of the centre of mass (COM) as identified by way of three dimensional motion capture system. The vertical force-time data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 17 Hz [21]. Retro-reflective markers were placed on each subject medial and lateral malleoli, tibial tuberosity, patella, greater trochanter, anterior and posterior superior iliac spine and a single marker placed on the spinous process of S2 for the calculation of whole-body COM [22]. Data was collected at 1000Hz on a 9-camera motion capture system (Qualisys AB, Gothenburg, Sweden). These data were then modelled using standard biomechanical software (Visual3D, C-Motion, Inc. Maryland, USA) to construct a four-segment body of the subject. A global reference system was established with the positive y-axis in the intended direction of the VJ, the x-axis perpendicular to the y-axis and the positive z-axis pointing vertically.

Previously classified common force platform based methodologies of VJ phase identification

Methods 1-3 use force platform data for phase identification and then calculation of force time variables from data and are as described by Eagles et.al [8]. Method 1 classifies the initiation of the jump (i.e. the beginning of the eccentric phase) as a 5% reduction in vertical ground reaction force (VGRF), or when CMJ testing was of multiple jumps in a row; as peak VGRF after landing from the previous jump. The end of the eccentric phase is defined as the minimum VGRF recorded prior to the large peak VGRF. The end of the eccentric phase is also the start of the concentric phase. The end of the concentric phase coincided with leave time and is defined as the point where VGRF becomes <5 N.

Method 2 defines the start of the jump as the point when the VGRF exceeded a quite standing value of the subject in newton's (typically 10 N or >GRF mean ± 5). From here the eccentric and concentric phases are determined by using a calculated (via the integration of the force time signal) orientation of the centre of mass. The eccentric phase starts when the calculated centre of mass starts descending, and ends when it reaches its lowest point. The latter also defines the start of the concentric phase, which subsequently ends when the participant leaves the force platform.

Method 3 also relies on the calculation of the centre of mass via the integration of force time data. The start of the eccentric phase in Method 3 is the same as for Method 2. However, Method 3 defines the end of the eccentric phase as the instant that the calculated COM has a velocity of 0 m/s. The beginning of the concentric phase of the jump is operationally defined as the point in which the calculated vertical velocity of the centre of mass exceeded 0.1 m/s, with the concentric phase ending at the point where the participant leaves the force platform.

Summary of methods

It is important to note that Methods 2 and 3 both calculate centre of mass position from the integral of the force time data [23]. The key differentiation between Methods 2 and 3 is that the latter incorporates a gap, or pause between the end of the eccentric and start of the concentric phases (Figure 1). Method 2 interprets the phases as one going directly into the other without a pause. Method 1 is essentially using the force time trace from the force platform data to determine phases by assuming the trace can be interpreted as a literal time line of the jump (Figure 1). Method 4 will refer to analysis by way of three dimensional motion capture system.

Statistical analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows, version 11.0; SPSS, Inc., Chicago, IL, USA). The mean of each participant 6 VJs were used for analysis. To compare EPT, CPT, TPF, RFD and MCF of the four different methods, a one-way ANOVA was used with a Scheffe post hoc to determine statistical differences between methods. The level of significance was set at $p<0.05$. Additionally a Person's product moment correlation coefficient was incorporated to examine the strength of association among each of the methods analysed. Correlations were described as trivial (0.0-0.1), low (0.1-0.3), moderate (0.3-0.5), high (0.5-0.7), very high (0.7-0.9), and practically perfect (0.9-1.0) [24].

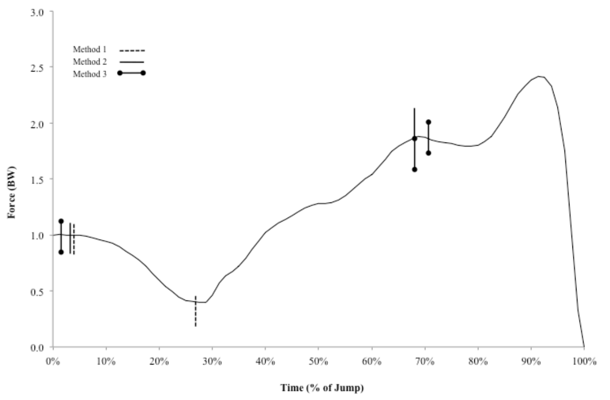

Figure 1: Graphical depiction of methods 1-3 for determining vertical jump phases using a force-time data set from a typical jumper selected from our participants. Each method's initial line indicates start of the eccentric phase (decent of COM), with the second line indicating the end of the eccentric and start of the concentric phase (ascent of COM). Note: Method 3 has three lines; the gap between the last two is the pause between phases, as Method 3 does not move directly from phase to phase. *Body Weight (BW).

Results

The results of the present study indicate that maximum concentric force (MCF) from methods 1-3 was not significantly different ($p<0.05$) compared to method 4 (Figures 2 and 3). The means and standard deviations for each method analysed can be observed in Figure 3. Method 1 was found to be significantly ($p<0.001$) different to Method 2, 3 and 4 for eccentric phase time (EPT), concentric phase time (CPT), TPF and RFD. Method 2 was significantly different from method 3 and method 4 ($p<0.05$) for EPT. Inter correlations for each method analysed can be observed form Figure 4. Correlations observed range from low 0.17 (RFD method 1 vs. method 4) to perfect 1 (MCF). Collectively methods 2 and 3 were very highly correlated to one another and to method 4 for each fore time variables analysed. Method 1 was moderate to highly correlate with the other methods but most poorly to method 4.

Discussion

The purpose of this study was to compare how vertical jump phase identification using the three-dimensional motion capture system [25,26] differs from three common force platform based methodologies. The results of the study indicate no force platform based methodology provides completely accurate identification of phases within the VJ movement. Methods 2 and 3 correlate very highly with one another and to the motion capture system. Method 1 correlates only moderately to methods 2, 3 and the motion capture system with motion capture system representing the weakest correlation (Figure 4). In particular method 1 failed to accurately identify the both phases of the VJ. Consequently key force time variables were significantly different between method 1 and method 4 and therefore method 1 represents an inaccurate method of VJ analysis (Figures 2 and 3).

No significant differences were found for maximum concentric force (MCF) with methods 1-3 compared to motion capture system (method 4). This would indicate that regardless of methodology used MCF remains consistent. Similar results have been found elsewhere with peak force values remaining consistent between various methods of VJ analysis [27]. While this is an important finding, variables such as TPF and RFD, both of which contain a time component, will be more predictive of performance in dynamic activities than variables that rely solely on peak force measures [10-14].

The RFD and TPF for method 1 were found to be significantly different compared to method 4 ($p<0.001$). Therefore these results question the accuracy of method 1 as a means to determine RFD and TPF and the inconsistencies in this method may explain the large coefficients of variation values for RFD and TPF found during the VJ [18,19,28]. The differences for RFD and TPF found in method 1 are most likely due to the identification of the concentric phase, which was significantly different, compared to method 4 ($p<0.001$) (Figures 2 and 3). While the end of the concentric phase is same for all methods as this corresponds to the unloading of the force platform, the differences found in method 1 are due to the initiation of the concentric phase, which in turn is dependent on when the eccentric phase is deemed to have ended (Figure 1).

For the eccentric phase methods 1 and 2 were found to be significantly different compared to method 4 (M1 $p<0.001$, M2 $p<0.05$) (Figures 2 and 3). The differences found in the EPT are primarily due to the identification of the end of the EPT as there are no significant differences in the start of the EPT among the methods 1-3. Method 1 classifies the end of the eccentric phase as the minimum VGRF recorded. Motion capture system analysis (method 4) has revealed that the body continues to undergo eccentric loading past the lowest VGRF point. Therefore taking the lowest VGRF value does not necessarily indicate the end of the eccentric phase and start of the concentric phase.

Methods 2 and 3 offer a reasonably reliable measure of VJ force time variables through their respective methods of phase identification within the jump. All methods offer reliable peak values, however extraction of more pertinent variables such as RFD and TPF are only available from methods 2 and methods 3 when comparing to motion capture system (method 4) [25,26]. Method 1 was found to be significantly different in all the force time variables with a time component, which was primarily due to the incorrect identification of the eccentric and concentric phases of the jump (Figure 1). While only method 1 has been identified as having significant error, this method has been referenced in the literature 122 times in various articles [8], which further reinforces the spread and confusion through inaccurate phase identification of the VJ. Research that uses the inaccurate calculation process of method 1 involves elite athlete groups as well as clinical populations [29,30]. Subsequently these articles themselves have been referenced, further spreading findings based on erroneous methodologies.

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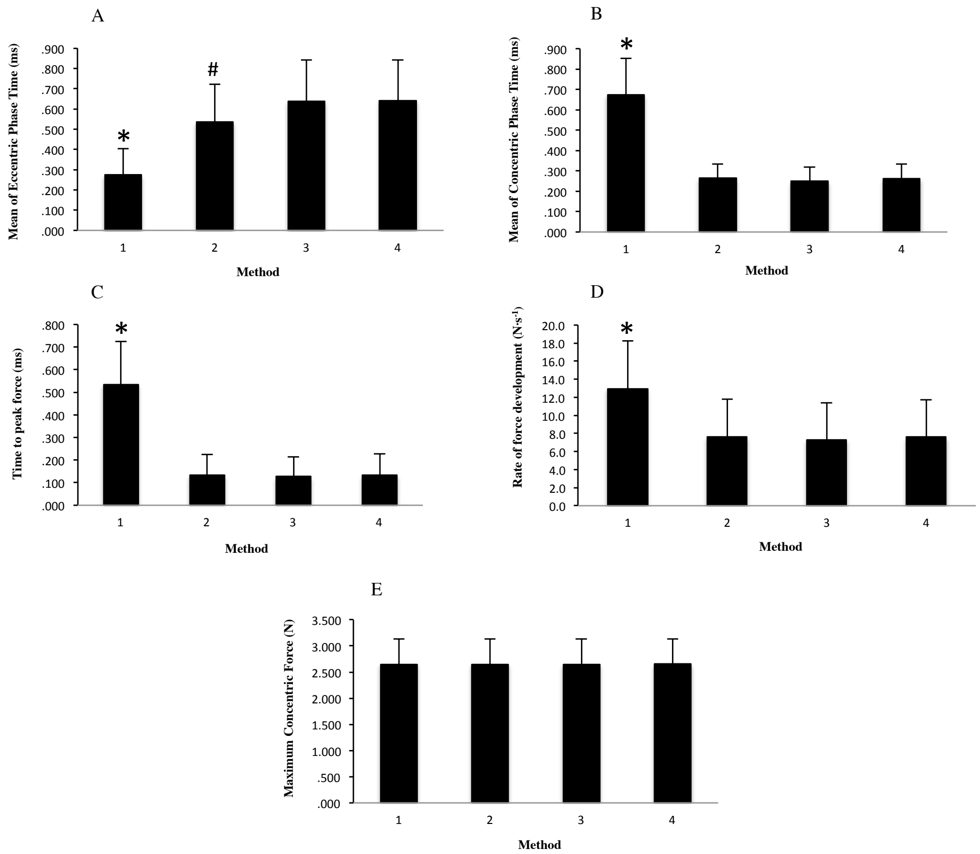

Figure 2: A comparison of force time variables between methods 1-4. Graphs A-E *p<0.001, #P<0.05. M1: method1, M2: method 2, M3: method 3, M4: motion captures system.

	Method 1	Method 2	Method 3	Method 4
EPT (ms)	0.27±0.13 §□¶	0.54±0.19 #▯⊙	0.64±0.20 #❖	0.64±0.20 #❖
CPT (ms)	0.67±0.18 §□¶	0.27±0.07 #	0.25±0.07 #	0.26±0.07 #
TPF (ms)	0.54±0.19 §□¶	0.13±0.09 #	0.13±0.09 #	0.13±0.09 #
RFD ($N·s^{-1}$)	12.96±5.32 §□¶	7.64±4.17 #	7.30±4.10 #	7.30±4.10 #
MCF (N)	2.65±0.48	2.65±0.48	2.65±0.48	2.65±0.48

#Significant difference from method 1 (p < 0.001) ★Significant difference from method 3 (p < 0.05)
¶Significant difference from method 4 (p < 0.001) □Significant difference from method 3 (p < 0.001)
▯ Significant difference from method 4 (p < 0.05) §Significant difference from method 2 (p < 0.001)
❖Significant difference from method 2 (p < 0.05)

Figure 3: Mean ± SD values for 4 methods of analyzing vertical jump force time variables*. *EPT=eccentric phase time, CPT=concentric phase time, TPF=time to peak force, RFD=rate of force development, MCF=maximum concentric force; ms=milliseconds, N=newtons, Ns^{-1} = newton seconds.

	Method 1 vs. Method 2	Method 1 vs. Method 3	Method 1 vs. Method 4	Method 2 vs. Method 3	Method 2 vs. Method 4	Method 3 vs. Method 4
	r	*r*	*r*	*r*	*r*	*r*
EPT (ms)	0.55	0.59	0.55	0.90	0.77	0.72
CPT (ms)	0.62	0.52	0.44	0.84	0.81	0.76
TPF (ms)	0.55	0.60	0.53	0.97	0.72	0.77
RFD ($N·s^{-1}$)	0.37	0.29	0.17	0.99	0.75	0.78
MCF (N)	1	1	1	1	1	1

*EPT = eccentric phase time, CPT = concentric phase time, TPF = time to peak force, RFD = rate of force development, MCF = maximum concentric force; ms = milliseconds, N = newtons, $N·s^{-1}$ = newton seconds.

Correlations were described as trivial (0.0–0.1), low (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), very high (0.7–0.9), and practically perfect (0.9–1.0).

Figure 4: Intercorrelations for calculated force time variables among methods 1-4.

Conclusion

No force platform based methodology for VJ phase identification and extraction of force time variables is entirely accurate. However in the absence of high quality infrared motion capture system analysis; methods 2 and 3 appear to provide the most reliable results when determining phase identification and performance variables for VJ data. Consequently questions remain over the accuracy of method 1 and therefore caution should be used when analysing VJ data with this method.

Limitations and Future Directions

This study used a lower body marker set to calculate each participants COM. Previous studies [25] have used more complete marker sets incorporating the upper body to calculate a participants COM. While the lower body marker set incorporating a S2 sacral marker has been shown to provide a reasonable estimation of whole body COM [22], future studies should analyses both marker placements to determine their level of agreement.

This study does not attempt to define the most appropriate method for VJ analysis. Rather a comparison has been made between commonly employed methods of VJ analysis in current use. Future research should continue to compare motion capture and force platform technologies with other devices such as inertial measurement unit, accelerometers and magnetometers.

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