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

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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
maximise 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].
Reflective markers were placed on each subject medial and lateral
deltoeii, 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
test 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].
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.
**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.

**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.

**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 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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