FORCE- VELOCITY AND POWER- VELOCITY RELATIONSHIPS

OBSERVED FROM LOADED VERTICAL JUMPS

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Biomechanics and Movement Science

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<td>95% Confidence interval</td>
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<td>Slope of the F-V linear regression</td>
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<td>Body weight</td>
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<td>Countermovement jump</td>
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ABSTRACT

The aims of the present study were to (1) explore the pattern of force-velocity (F-V) relationship of leg muscles, (2) evaluate the reliability and concurrent validity of the obtained parameters, and (3) explore the load associated changes in the muscle work and power output. Subjects performed maximum vertical countermovement jumps with a vest ranging 0-52% of their body mass. The ground reaction force and leg joints kinematics and kinetics were recorded. The data revealed a strong and approximately linear F-V relationship (individual correlation coefficients ranged from 0.69–0.93). The relationship slopes, F- and V-intercepts, and the calculated power were moderately-to-highly reliable (0.67 < ICC < 0.91), while their concurrent validity with respect to the directly measured values was on average moderate. Despite a load associated decrease in both the countermovement depth and absolute power, the absolute work done increased, as well as the relative contribution of the knee work and power as compared with the hip and ankle. Therefore, the loaded vertical jumps could be developed into a routine method for testing the mechanical properties of leg muscles, while the load associated changes in both the absolute and individual joints’ work and power could reveal the mechanisms of adaptation of multi-joint movements to different loading conditions.
Chapter 1

GENERAL INTRODUCTION

During any real world movement task, muscles have to overcome both inertia and weight of its body to produce motion. External loads are known to affect acting muscle forces and, consequently, mechanical patterns of various movements (Pazin et al., 2013). For the given level of muscle excitations, there are a number of kinematic factors affecting muscle force, such as muscle length and velocity of its contraction. Since seminal work done by Fenn and Marsh exploring the mechanical properties of voluntary muscle contractions, there are generally accepted relationships between the velocity of shortening and how much tension that muscle group can exert (Fenn and Marsh, 1935). Further exploration of muscle mechanics reveals generally an accepted force-velocity ($F-V$) relationship of 'in vitro' muscles as hyperbolic, with maximal force decreasing with increased velocity of shortening (Hill, 1938; Wilkie, 1950). These hyperbolic modeling results were seen again in vivo muscular contractions of single joint muscles (Duchateau J and Hainaut, 1984). Similarly, $F-V$ relationship can also be used to derive the power-velocity ($P-V$) relationship of muscles, where $P$ is calculated as product of $F$ and $V$ obtained from $F-V$ relationship. The classic Hill's hyperbolic $F-V$ relationship reveals a somewhat complex $P-V$ relationship where maximal $P$ is obtained when acting against moderate loads. This complexity may
somewhat limit the ability to utilize these relationships in rehabilitation and training (Jaric, in press).

It is well known that muscular systems also maximize power output with maximum effort against moderate external loads. Since the optimum load that enables maximization of muscle power output could correspond to a certain percent of muscle strength, that muscle mechanical property may be referred to as 'strength dependent behavior' (Jaric and Markovic, 2013). However, recent evidence suggests that leg muscles may exhibit a strength independent behavior, with maximal power being produced at one’s own body weight independently of leg muscle strength (Jaric and Markovic, 2013; Nuzzo et al., 2010; Samozino et al., 2014; Suzovic et al., 2013). Partial explanation for this strength dependent behavior could come from the potential linear $F-V$ relationship.

Since the discussed muscle mechanical properties have been mainly studied on in vitro muscles and single joint movements, it is of great importance that we look to understand how more complex, multijoint tasks may be modeled with $F-V$ and $P-V$ relationships. It is important to understand how these relationships are modeled in ecologically valid movements such as the vertical jump. Namely, the vertical jump represents an important motor activity frequently employed in many sports and training routines daily, and has a similar kinematic pattern to gait. It is important to understand how the mechanical properties of muscles in multijoint tasks could be modeled in real world conditions in order to design training procedures aimed to
maximize power. The vertical jump may provide a model that is suitable for exploration of multijoint $F-V$ relationships. Evidence has been presented that improvements in power can be detected by improvements in vertical jump height and further; they are correlated with sprint running improvements (Marques and Izquierdo, 2014). This relationship between sprint running and vertical jumping demonstrates how information regarding the vertical jump may be generalized to other ballistic performance, and validates the use of the vertical jump as a predictor for power.

Therefore, the maximum vertical jumps could be particularly valid model for studying muscles' mechanical properties. If a linear model is well fit for $F-V$ relationships, it could provide the basis for more simple and routine testing of force, speed, and power producing capabilities of the legs.

The linear model of $F-V$ relationships reveals this relationship:

$$F(V) = F_o - aV$$

where $F_o$ is the F intercept at a zero velocity, $a$ is the slope ($F_o/V_o$), and $V_o$ is the maximal velocity at zero force. This would result in a parabolic $P-V$ relationship:

$$P(v) = F(v) V = F_o V - aV^2$$

As a consequence, the $Po$ is obtained at

$$Po = (F_o V_o)/4$$

Maximizing power output has been of profound importance for many athletic trainers, sport coaches and therapists. A linear $F-V$ relationship would reveal an associated parabolic $P-V$ relationship with maximal power occurring at precisely one
half of the maximal $V$ and one half the maximal $F$. This has applications in both training and rehabilitation. From a rehabilitation perspective, practitioners could use the linear $F-V$ relationships to measure maximal force, speed, and power increases with training in a routine test. From a training application, individuals could monitor their training progress as well as better understand what loads to utilize in training to maximize power output. In order to improve power-trained athletes, it is imperative to know at what load they produce maximal power (Smilos et al., 2013). It has been often proposed that in order to train for power events, an athlete should train under conditions where the power output may be maximized (Cormie et al., 2011a; Markovic and Jaric, 2007; Samozino et al., 2012). Some studies have shown possible peaks of power at weights below the body weight as a result of unloading the athlete (Jaric, in press). Results from other studies have found maximal power output to be achieved at intermediate loads from 0- 59% (Jaric and Markovic, 2013). A possible explanation of these inconsistencies is that not all studies have used ecologically valid movements as resistance is often applied, but not inertia. Furthermore, studies have inconsistently taken into account the mass of one’s own body, or positioning external load far from the body's center of mass (Jaric and Markovic, 2013).

While most of the studies conducted on in vitro muscles and single-joint movement have revealed a hyperbolic relationship between force and velocity, there is conflicting evidence regarding whether multijoint movements could be modeled by a different approach. Namely, the $F-V$ profiles of multijoint tasks could be linear rather
than hyperbolic (Bobbert, 2012; Cuk et al., 2014). Linear relationships have been observed in multijoint tasks such as sprinting in cycling (peak pedal force and crank velocity) (Driss, et al., 2002), double leg push offs from a sledge (Samozino, et al. 2012), and vertical jumps (Bobbert, 2012; Cuk, et al., 2014). In a work done by Cuk and co-workers (2014), resisted vertical jumps were used to test the F-V and power-load relationships of the jumps. High correlations (R > 0.9) were found using obtained parameters ($F_o$, $V_o$, and $P_o$) from the linear relationships to model both average and maximal F-V profiles in vertical jumping. In this study, resistance was applied with stretched bands and three types of jumps were used (Cuk, et al., 2014).

The results of the present yielded similar F-V patterns, but both weight and inertia were applied to the subjects with the use of a loaded vest, so the results could be more ecologically valid (Aim1). In 2012 Pierre Samozino found similar linear F-V relationships for subjects doing a two-legged, seated, push off at different slopes. They further suggested that individuals might have different F-V profiles, for those more inclined towards high force or high velocity. These differences could begin to provide the basis for development of training protocols based on F-V relationships. Not only are the relationships linear, but also they show a clear difference in how they may perform the task (Samozino, et al., 2012). This is evidence that the vertical jump may be used to detect differences in strength (aim 3).

As subjects perform movements with an increase in external load, we expect joint kinetics and kinematics to change substantially. These changes could help to
understand both the linearity of the $F-V$ relationship as well as the strength independent behavior of the legs in jumping. By quantifying joint work and power as load increases, this study provides insight into compensation mechanisms made at the joint level to counteract the external load. Changes in power may be due to different jumping kinematic patterns, such as subjects going into a shallower squat in heavier loads, or it could be due to muscle and neural input adaptation (Jaric, in press). Recent work in soldier cutting maneuvers with loaded backpacks revealed a marked increase in knee power as load increased (Brown, et al., 2014). This finding is important for two reasons; first, it could allow for better understanding of adaptations the human body undergoes when additional load is placed on it, and secondly, allows for awareness of how joints respond to additional load for training and rehabilitation purposes (aim 4). If the knee extensor muscles produce more of the power at heavier loads, it may be possible to use this information to train the knee extensor muscles as well as important for individuals to avoid heavy loads if they have ACL or knee injuries.

Lastly, by measuring work and power produced by the center of mass (COM), we quantified the effectiveness of adjustments made at the joint level to total work and power producing capabilities of the body.
Chapter 2
SPECIFIC AIMS

The force-velocity \((F-V)\) and power-velocity \((P-V)\) relationships of skeletal muscles have been studied for almost a century. They have been typically modeled with a hyperbolic and parabolic regression, respectively, in both 'in vitro' muscles and in single-joint voluntary tasks. The patterns of \(F-V\) and \(P-V\) relationships generally reveal basic mechanical properties of skeletal muscles. Therefore, they are believed to provide not only an insight into the general design of individual muscles, muscular systems and the processes of their adaptation, but also serve both for studying muscular coordination and for various kinds of biomechanical modeling.

Maximum vertical jumps represent one of the most often studied motor tasks. They have been typically employed for purposes such as the assessment of mechanical properties of leg muscles, or for their training and testing. Their importance has been partly based on findings that the kinematic pattern of vertical jumps partly corresponds to the same patterns of gait, while the maximum performance of vertical jumping and sprinting highly correlate. However, both the complex musculoskeletal structure involved in vertical jumps and the diversity of jumping patterns and their adaptations typically constrain development of relatively simple methods for the assessment of force, velocity and power producing capacities of leg muscles.
Recent research suggests that simultaneous leg extension could provide the data that could serve for the assessment of mechanical properties of leg muscles. Namely, an increase in external resistance (e.g., a load added or externally applied force) inevitably lead to an increase in ground reaction force and decrease in velocity of the center of mass, which allows for modeling the $F$-$V$ and, consequently, $P$-$V$ relationship. Moreover, the $F$-$V$ relationship could be fairly liner, while $P$-$V$ relationship could reveal maximum $P$ in the vicinity of 'zero-load' independently of leg muscles' strength. However, the possibility of using natural vertical jumps loaded by added mass for the purpose of assessing $F$-$V$ and $P$-$V$ relationship has been largely neglected.

The aim of this study is to explore the mechanical properties of leg muscles through the kinematic and kinetic patterns of loaded maximum vertical jumps, as well as through the related $F$-$V$ and $P$-$V$ relationships.

**Specific aim 1:** To assess patterns of $F$-$V$ and $P$-$V$ relationships of leg muscles through loaded maximum vertical jumps.

**Hypothesis 1A:** The data will reveal approximately linear $F$-$V$ relationship.

**Hypothesis 1B:** $P$-$V$ relationships will reveal a $V$ associated increase in $P$.

**Specific aim 2:** To assess the reliability of the $F$-$V$ relationship.

**Hypothesis 2:** A test-retest design will reveal reliable parameters (i.e., maximum force ($F_o$), maximum velocity ($V_o$), and maximal power ($P_o$)) of $F$-$V$ relationship.
**Specific Aim 3:** To investigate the concurrent validity of the $F-V$ relationship.

**Hypothesis 3A:** Maximum force and maximal power obtained from $F-V$ relationship will be positively related with strength and power of knee muscles, respectively.

**Hypothesis 3B:** Maximum power and maximum velocity calculated from the $F-V$ relationship will be positively related with the directly measured power output and jump height, respectively.

**Specific aim 4:** To explore the contribution of work and power of individual leg joints to the total work and power output.
Chapter 3

3.1 Introduction

A number of recent studies have been focused on the mechanical properties of muscles during multijoint tasks (Bobbert, 2012; Cormie, et al., 2011a; Jaric, in press). The outcomes could be of apparent interest since it allows for better understanding mechanical properties of the muscular system, as well as for its potential applications in rehabilitation and training (Cormie, et al., 2011a).

Since seminal work done by Fenn and Marsh (1935) and Hill (1938), the dependence of muscle force ($F$) upon its velocity ($V$) of shortening (i.e., the $F$-$V$ relationship) of both in vitro muscles and individual muscle groups has been studied. It has been generally considered to be hyperbolic in shape (Hill, 1938; Wilkie, 1950). Since power ($P$) is the product of $F$ and $V$, the associated power-velocity ($P$-$V$) relationship is of a complex shape revealing the maximal $P$ ($P_0$) when the tested muscles act against moderate external resistance. The complexity of the pattern of both relationships is an apparent limiting factor for both optimization and testing procedures in rehabilitation and athletic training protocols, as well as in muscle and movement modeling. However, recent studies have provided the evidence that a linear $F$-$V$ relationship may be an appropriate model when testing maximum performance multi-joint movements, such as jumping (Cuk, et al., 2014; Samozino, et al., 2012;
Vandewalle, et al., 1987) cycling (Driss, et al., 2002), horizontal push offs from a sledge (Samozino, et al., 2012), and running (Morin, et al., 2013; Yamauchi, et al., 2009). The simplicity of the presumably linear $F-V$ relationship could have use in both practical applications and basic research. For example, the linear $F-V$ relationship observed from either cycling or vertical jumping could be used to develop a routine testing protocol for the assessment of the force, speed, and power producing capabilities of the legs. However, with the exception of a recent study conducted on vertical jumping (Cuk, et al., 2014), the reliability and concurrent validity of the linear $F-V$ relationship parameters still remains largely unknown.

Note that the vertical jumping pattern mimics simultaneous leg joints flexion and extension typical for running, while the jumping performance highly correlate performance (Kukolj, et al., 1999; Marques and Izquierdo, 2014). Therefore, the loaded vertical jumping could be developed into a more ecologically valid test of the mechanical properties of leg muscles than the tasks such as cycling (Driss, et al., 2002) of maximum push-offs (Samozino, et al., 2012). However, although a number of studies have routinely applied the linear regression model to fit the range of obtained $F$ and $V$ data from the loaded vertical jumps (Driss, et al., 1998; Samozino et al., 2014; Vandewalle, et al., 1987) the linear model has not been properly evaluated and compared to non-linear ones. Therefore, the linearity of the $F-V$ relationship still remains questionable. Furthermore, a variety of loading methods have been employed to test the $F-V$ relationship. For example, stretched elastic bands were used to provide approximately constant resistive force but not inertia (Cuk, et al., 2014; Yamauchi, et
al., 2009). Note that the added weight, inertia, and their combination could have distinctive effects of the force and power output of maximum vertical jumps (Leontijevic et al., 2012). Furthermore, Smith machine adds weight on the subjects’ shoulders that alters relative loading of different body segments (Samozino, et al., 2012), while push-offs alters conditions for action of leg muscles and eliminate involvement of actions of trunk and upper body muscles (Samozino, et al., 2012; Yamauchi, et al., 2009). Therefore, exploring the effects of loaded vest added on the chest could deserve an attention regarding their possible use in the future assessment of the $F-V$ and $P-V$ relationships. Namely, loaded vests are not only widely available within clinics and testing settings, but they also add weight close to the body center of mass and, therefore, may not alter movement pattern as much as other loaded methods could.

In addition to methodological problems discussed above, there is apparent need for understanding the mechanisms that lead to approximately linear $F-V$ (and, consequently, parabolic $P-V$) relationship of the multi-joint movements. Although the possible role of the load associated changes in the pattern of muscle activation have been proposed, recent modeling study suggests an important role of segmental dynamics, particularly in the tasks based on simultaneous extension of leg joints, such as in jumping and push-offs. However, the jumping kinematic pattern is typically adapted to an increased external load by altering individual joint angles and, in particular, by reducing the countermovement depth over the eccentric jump phase (Markovic, et al., 2014; Yamauchi, et al., 2009). The countermovement depth even if
altered within relatively wide margins, may not affect the jumping performance, but markedly affects the force, work, and power output of both individual joints (Brown, et al., 2014) and entire body (Mandic, Jakovljevic, and Jaric). Therefore, the contribution of individual joints to the absolute work and power produced could reveal both the mechanisms of adaptation of the jumping pattern to the altered external load and their role in the observed $F-V$ relationship.

To address the discussed problems, we studied loaded vertical jumps with the aims (1) to explore the pattern of $F-V$ relationship, (2) to evaluate the reliability and concurrent validity of the obtained parameters with directly measured values, and (3) to explore the load associated contribution of individual joints to the absolute work and power output. The findings of this study are expected not only to advance our knowledge regarding the design and function of the muscular system, but also to contribute to further development of routine tests of speed, force, and power producing capabilities.

3.2 Methods

3.2.1 Subjects

Using guidelines from Cohen (Cohen et al., 2003) we conducted a sample size analysis based on the effects of external load on force, velocity and power output (Cuk, et al., 2014; Markovic and Jaric, 2007). It appeared that 3-9 subjects would be needed for statistical power 0.8 and an alpha level 0.05. Conservatively, we recruited 11 physically active male subjects with BMI between 20 and 25. However, one subject was excluded due to major problems with jump coordination that led to highly
inconsistent data. The remaining 10 subjects (age 21.9 ± 3.2 years, weight 72.2 ± 5.4 kg, and height 1.78 ± 0.12 m; BMI of 22.8 ± 1.2; data presented as means ± SD) were devoid of any neurological impairments and musculoskeletal injury in the previous 6-months. Nine were categorized as ‘highly active’, while one as ‘moderately active’ on the IPAQ questionnaire (Craig et al., 2003). None of the subjects was an active athlete. All participants signed a written informed consent in accordance with the Declaration of Helsinki and the University of Delaware IRB.

3.2.2 Experimental Protocol

Each subject completed two sessions with at least 48- hours and no more than 72- hours separating sessions. Both sessions began with 5- minutes warm up on a stationary bike followed by 5- minutes of dynamic stretching. During the first session, the anthropometric data was taken and, thereafter, the isokinetic knee extensor strength was tested on a Kin- Com isokinetic dynamometer (Chatex Corp., Chattanooga, Tennessee, USA). The remaining part of the first session was used for familiarization with vertical jumping performed with different external load.

The second session involved only the tests of loaded vertical jumps. Identical protocol was used as in the first session. Specifically, two consecutive series of trials of 18 jumps for a total of 36 jumps (2 series x 9 loads x 2 trials each). The first trial at each load was used for habituation and the second one was taken for analysis.

3.2.3 Experimental Procedure
Body mass and height were assessed with an analog scale and height using a standard anthropometer and mass was verified on the force plate in quiet standing prior to each jump.

For isokinetic testing, each subject performed 10 knee extensions at each of the angular velocities of either 60 °/s or 120 °/s. performed in random sequence. First five trials were used for habituation to the speed and full (20 seconds) rest was given after each trial. The average peak torque was recorded from the second five trials. Verbal encouragement was given during each trial.

Regarding the jumping portion of the experiment, subjects were instructed to perform maximal countermovement jumps with the use of an arm swing. The nine loading conditions were randomized for each subject. Specifically, a MiR© pro loaded vest (MiR, San Jose, CA, USA) with loading capabilities from 0- 60 lbs (0-27.3 kg; 0 to 52% of averaged subjects body mass) was employed to manipulate external load. Pairs of 1.81 kg (4lbs) weights were added at a time, symmetrically to create eight loading conditions from 0- 25.5 kg in 3.62 kg increments, and one more 1.81 kg weight to make the ninth condition, 27.27 kg. In line with recent studies with conducted with similar loads, (Cuk, et al., 2014; Markovic and Jaric, 2007; Pazin, et al., 2013) subjects were given 30- seconds between 2 trials with the same load, and approximately 2- minutes between different loads and fatigue was not an issue. None of the subjects reported fatigue.
3.2.4 Data Acquisition and Processing

Participants performed the jumps on a force plate (Bertec FIT, Columbus, Ohio, USA) with a 6-degree of freedom marker set on their legs and pelvis (33-reflective markers) with 7-Eagle cameras to collect motion data. Force and motion data were sampled together at 240 Hz and low pass filtered (2\textsuperscript{nd} order recursive Butterworth filter, with a cutoff frequency of 12 Hz). Joint position was calculated from 33 reflective markers, and a kinematic model of seven body segments (bilateral foot, shank, thigh, and single pelvis) with 6 degrees of freedom was defined from a stationary recording. The data were collected in Cortex (Motion Analysis Inc.) and analyzed in Visual 3D (C-Motion Inc.) using custom designed pipeline commands to assess kinetic (joint work and power) and kinematic (time, velocity, force) variables.

The vertical component of the ground reaction force was recorded and low pass filtered (2\textsuperscript{nd} order recursive Butterworth filter with a cutoff frequency of 12 Hz). The filtered positions of the 3D markers were assessed frame by frame in Visual 3D. Velocity and position of the center of mass were assessed by two integrations of the acceleration signal obtained from the recorded ground reaction force. Average values of force and velocity were recorded during the subjects’ concentric phase of the vertical jumps. Maximum $P$ ($P_{\text{max}}$) was calculated as the product of recorded $F$ and calculated $V$ averaged across the concentric jump phase, while work was calculated as the integral of $P$.

The linear regression model
\[ F(V) = F_0 - aV \]  

was applied on the range of \( F \) and \( V \) data obtained from different loads, where \( F_0 \) is the \( F \)-intercept at a zero velocity (i.e., the maximum \( F \)), \( a \) is the slope \( (F_0/V_0) \), and \( V_0 \)-intercept at zero \( F \) (i.e., the maximum \( V \)). Finally, note the maximum \( P \) equals

\[ P_0 = (F_0 V_0)/4 \]  

While the linear models were applied on both individual and averaged across the subject data, a \( 2^{nd} \) order polynomial model was also applied but only on the averaged data. The corresponding coefficient of determination (r\(^2\)) were calculated for all regression models, as well as their 95% confidence intervals.

### 3.2.5 Statistical Analysis

To assess reliability of the obtained parameters of the linear model from 2 consecutive series of jumps, standard error of measurement (SEM), coefficient of variation (CV), intraclass correlation coefficient (ICC), and paired t-tests were calculated for each of the four obtained parameters obtained from the linear model \( (F_0, V_0, a, \text{ and } P_0) \) applied on the second series of jumps. Pearson correlation was employed to assess concurrent validity between \( V_0, P_0, \) and \( F_0 \) with, respectively, directly measured values of maximal velocity \( (V_{\text{max}}) \) and power \( (P_{\text{max}}) \) obtained from jumps performed with 0 load, and torque \( (F_{\text{max}}) \) from the isokinetic dynamometer at two speeds. Linear regression models were used to assess the load associated changes in the absolute and relative work and power of the entire body and three individual leg joints.
### 3.3 Results

The vertical component of the ground reaction force is shown in Figure 1 for 3 external loads. As expected, an increase in additional load is associated with an overall increase in the recorded force.

![Ground reaction force at three loads](image)

**Figure 1**  Vertical component of the ground reaction force obtained from a representative subject loaded by 0, 14.5 and 27 kg. The data are aligned according to the instant of transition from eccentric to concentric phase of jump (see dashed vertical line).

Figure 2 shows averaged across the subject changes in kinematic variables associated with an increase in applied load. The applied regression model reveals a load associated decrease in both the countermovement depth and jump height. However, despite the decreased countermovement depth, the duration of the concentric jump phase increases with the applied load.
Figure 2 Load associated changes in kinematic variables (data averaged across 10 subjects; means with SD error bars). Top panel shows the jump height and countermovement depth, while the bottom panel shows the duration of the jump concentric phase of the jump (**\( p < .001 \)).

Figure 3 shows the main finding of the study through the \( F-V \) relationships obtained from the averaged across the subject data obtained from 9 individual loads. Specifically, when averaged across the concentric jump phase, a load associated increase in ground reaction force (\( F \)) is also associated with a decrease in velocity of the center of mass (\( V \)). The data are fitted with both a linear and 2\(^{nd}\) order polynomial
Figure 3  Average across the subjects values of force and velocity (means with SD error bars) obtained from the concentric phase of the vertical jumps performed with nine loads. The linear regression line and 2nd order polynomial line are shown with the corresponding correlation coefficients and their 95% confidence intervals (** p < .01).

regressions. The coefficient of determination ($r^2$) and the corresponding 95% CI are shown. Both regression models reveal strong and highly significant relationships. Of importance could be that neither of the $r^2$ falls out of the 95% CI of $r^2$ of another model suggesting no significant difference between them.

The linear $F-V$ relationships were also obtained from individual data. The coefficients of correlations ranged from 0.69 to 0.95 (median value 0.79). Their parameters obtained from 2 consecutive jumps allowed calculating their indices of reliability (Table 1). ICC values proved to be either high (ICC>0.8 for $V_0$ and $P_0$) or moderate (0.6<ICC<0.8 for $F_0$ and $a$) with no differences between the consecutive trials. SEM and CV values were lower for $F_0$ and $P_0$, than for $V_0$ and, particularly, $a$. 
Table 1  Reliability measures between two trials for obtained parameters from linear $F-V$ relationship. CV (coefficient of variation), SEM is (standard error of measurement), ICC (intraclass correlation coefficient).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>CV (%)</th>
<th>SEM</th>
<th>ICC</th>
<th>T-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_0$</td>
<td>2626 ± 440</td>
<td>2431 ± 373</td>
<td>9.96</td>
<td>2</td>
<td>0.72 (0.21,0.92)</td>
<td>1.76</td>
</tr>
<tr>
<td>$V_0$</td>
<td>3.98 ± 1.72</td>
<td>4.12 ± 1.36</td>
<td>17.28</td>
<td>0.71</td>
<td>0.93</td>
<td>-0.636</td>
</tr>
<tr>
<td>$P_0$</td>
<td>2476 ± 703</td>
<td>2441 ± 462</td>
<td>8.4</td>
<td>220.3</td>
<td>0.68,0.98</td>
<td>0.238</td>
</tr>
<tr>
<td>$a$</td>
<td>-849 ± 462</td>
<td>-644 ± 245</td>
<td>30.23</td>
<td>83.86</td>
<td>0.11,0.90</td>
<td>-2.02</td>
</tr>
</tbody>
</table>

Figure 4 shows concurrent validity of $V_0$, $F_0$, and $P_0$ regarding, respectively, the directly measured velocity from the unloaded vertical jump (2.97 ± 0.93 m/s; mean ±SD), knee extension torque tested on the Kin-Com dynamometer at 60 and 120 °/s (217 ±11.9 Nm, and 198 ±10 Nm, respectively) and average $P$ directly recorded from the concentric phase of the unloaded jump (2127 ± 290 W). The obtained Pearson correlation coefficients were high for $V_0$ and $P_0$. The same values for $F_0$ when related with $Fmax$ exerted at 60 and 120 °/s on a Kin-Com revealed moderate values that were somewhat below the significant level.
Figure 4 Concurrent validity of $F-V$ relationship parameters with respect to the directly measured variables. The data show the correlation coefficients with the corresponding 95% CI error bars (* p < .05).

Figure 5 shows that while the absolute work increases, the absolute power decreases with load increase. Regarding the relative contribution of individual joints, the data suggest a load associated increase in both knee work and knee power, while the relative contribution of the ankle and hip reveals no significant trend. Finally, note that 3 leg joints contribute between 75% and 90% of the absolute work and power over the entire load spectrum.
Top panels show the load associated changes in the absolute work and power produced by the entire body, and by the hip, knee, and ankle joint. Bottom panels show the same changes in the relative contribution of hip, knee, and ankle joint to the absolute work and power (* p < .05)

3.4 Discussion

Within the present study we manipulated the mass of a loaded vest to obtain a range of $F$ and $V$ data that could reveal the $F$-$V$ relationship of leg muscles. Regarding the specific aims of this study, the results reveal that (1) the obtained $F$-$V$ relationship is exceptionally strong and fairly linear, (2) the relationship parameters could be
moderately-to-highly reliable and their concurrent validity could be on average moderate, while (3) the load associated increase in absolute work and decrease in absolute power is also associated with an increased relative contribution of knee joint.

The results revealed exceptionally high correlational coefficients for the linear $F-V$ relationships obtained both from the averaged and individual data. This finding is in line with findings obtained from both loaded vertical jumps (Cuk, et al., 2014) and other tasks performed predominantly by lower body muscles. Nevertheless, note that similar to a number of previous studies the range of obtained $F$ and $V$ data covers relatively small portion of their entire intervals (Samozino, et al., 2012; Yamauchi, et al., 2009). This limitation, as well as a pattern of the data hinting a somewhat curvilinear shape generally suggest that the linearity of $F-V$ relationship still need further support both regarding the tested vertical jumps and other multi-joint movements. Conversely, the relative importance of the obtained data could be based on its ecological validity. First, the tested vertical jumps could be more natural way for testing leg muscles than other leg tasks (e.g., push-offs and cycling; (Driss, et al., 2002; Yamauchi, et al., 2009). Second, the applied method of loading adds mass close to the center of gravity that makes it less likely to markedly alter the jumping kinematic and kinetic patterns, such as weight bars added to shoulders or an external constant loading force (Cuk, et al., 2014; Markovic and Jaric, 2007; Nuzzo, et al., 2010; Samozino, et al., 2012; Suzovic, et al., 2013).

Despite the limitation discussed above, the data add to the evidence that the reliability of the obtained parameters obtained from the linear $F-V$ regression model
could be high. Somewhat lower indices of reliability then obtained from the jumps loaded and unloaded by stretched rubber bands (Cuk, et al., 2014) could be a consequence of the different loading method or, alternatively, from a lower level of jumping skill of the subjects tested in the present study. Note also that in line with previous study (Cuk, et al., 2014) the reliability of $F_0$, $V_0$ and $P_0$ could be higher than the reliability of $a$. This could represent a methodological problem when assessing the optimal $F-V$ slope for optimizing individual performance (Samozino, et al., 2014; Samozino, et al., 2012). Regarding the concurrent validity, the obtained parameters for $V_0$ and $P_0$ were moderate-to-highly correlated with the directly measured velocity and power, while the same validity of $F_0$ was somewhat lower. Nevertheless, it should be kept in mind that the predictive power of standard tests of force, velocity and power regarding the performance of functional movements is on average moderate at best (Cormie, et al., 2011b; Jaric, 2002).

Particularly novel findings of the present study are related to the load associated changes in the absolute work and power, as well as to the relative contribution of individual joints. A decrease in absolute power associated with an increase in added load is in line with previous studies (Jaric and Markovic, 2009; Markovic and Jaric, 2007; Nuzzo, et al., 2010; Suzovic, et al., 2013) and could be explained by a specific design of leg muscles that maximize the power output when acting against the load imposed by the mass of one's own body (Jaric and Markovic, 2009, 2013). However, despite the decrease in the absolute power, the absolute work done increases with the added load. From the mechanical point of view, the increase in
the added load should overcompensate for a reduced countermovement depth (see Figure 2) resulting in a larger work, while the reduced velocity due to the larger load results in a lower power. This could shed additional light on the optimization of jumping and other complex movement patterns that have been widely extensively studied (Bobbert and van Soest, 2001; Cormie, et al., 2011a; Van Soest, et al., 1994). The increased contribution of the knee, as compared to hip and ankle is in line with the findings observed from the cutting and other dynamic maneuvers (Brown, et al., 2014). To gain a deeper insight into the mechanisms contributing to a higher involvement of the knee joint into producing the absolute work and power under higher loads, future studies should explore the load associated adaptation of kinematics of individual segments, rather than only the countermovement depth.

To conclude, the present findings reveal a strong and approximately linear $F-V$ relationship, and consequently, parabolic $P-V$ relationship of the leg muscles tested through loaded vertical jumping. Taking into account on average a high reliability and moderate concurrent validity of the obtained parameters, as well as ecological validity of the applied approach, the tested task may be utilized in routine testing of the force, velocity and power producing capacities of leg muscles. From the theoretical point of view, the load associated changes in both the absolute and individual joints’ work and power could reveal the mechanisms of adaptation of maximum performance multi-joint movements to different loading conditions.
Chapter 4

GENERAL CONCLUSIONS

Vertical jumping is a routine activity and allows for insight into the mechanical properties of the human musculoskeletal system. The ability of muscles to exert a high force, velocity, and power is crucial for both optimization of movement patterns as well as rehabilitation. Single joint F-V relationships may limit our understanding and application of this relationship in multijoint movements. Better understanding of this relationship could provide the basis for beginning to develop routine testing procedures for force, speed, and power producing capabilities of individuals.

In this study, we studied the effects of increasing load on kinetic and kinematic patterns in vertical jumping. Namely, an increase in load gives an obvious increase in ground reaction force in the vertical direction, and a decrease in velocity of the center of mass. Using 9 loading conditions from 0 kg to 27.3 kg (approximately 0-40% body weight), we were able to fit both linear and 2nd order polynomial regressions to average F-V data across 10 subjects. The linear fit appeared to be fairly appropriate for modeling F-V relationships in vertical jumping. From this, the four obtained parameters from the linear model \((F_0, V_0, a, \text{ and } P_0)\), were tested for reliability and concurrent validity. With regards to reliability, the obtained parameters were moderate to highly reliable in a test-retest protocol. In regards to concurrent validity, \(V_o\) and Po
had moderate to high concurrent validity as assessed through Pearson correlation, but $F_o$ had low concurrent validity. Lastly, in an effort to understand how individual joint work and power changes as load increases, regression models revealed a fairly strong relationship between increase in external load and increases in knee work and power. Furthermore, as load increased, total power decreased, while total work increased.

Overall, the results from this study suggest that a linear F-V model may be appropriate for vertical jumping, and the obtained parameters are fairly high in reliability, while the Vo and Po variables also have moderate to high concurrent validity. This information may be utilized in the development of routine testing for maximal force, velocity, and power producing capabilities for individuals. Further, the obtained parameters from this model could be used to track progress of a training program to elicit increases in velocity or power.

In regards to total work and power done by the system, a particularly novel finding was that work increased with an increase in load, while power decreased. A decrease in power has been observed in many other works (Jaric and Markovic, 2009), but work has not been quantified. Because all jumps were performed as maximal efforts, this increase in work could have roots in adaptations of the human body to mitigate losses in jump height by additional load. As load increases, subjects adopt different jumping mechanics that may optimize their potential work production capabilities at that load. Lastly, with regards to individual joint work and power, it is of theoretical importance to understand how the human body adapts as additional load is placed upon it. The results suggest that the knee is responsible for more of the total
work and power production as load increases. This may be an insight into mechanical adaptations of the lower legs to mitigate losses by increases in total load. If the knee were to produce as much work at the no load condition, the jump may not be performed in the correct manor (eg. not straight up). This information may be useful in designing rehabilitation and training procedures to either target increases in knee function, or limit potential injuries to the knee, as well as provide more theoretical insight into the adaptations the human body makes under heavy loaded conditions.

With regards to future research, experiments could test the same individuals over different multijoint tasks such as bench press throws, cycling, and jumping and compare individual F-V relationships. Future work should also help to understand if the F-V relationship may be appropriately modeled with a linear function, as it is still somewhat of a remote extrapolation from a relatively narrow range of data.
REFERENCES


Duchateau J & Hainaut, K., 1984. Isometric or dynamic training: differential effects on mechanical properties of a human muscle. 56 (2), 296-301.


Appendix A

INFORMED CONSENT FORM

University of Delaware
Informed Consent Form

Title of Project: Force-velocity and power-velocity relationships observed from maximally loaded vertical jumps

Principal Investigator (s): Daniel Feeney, Slobodan Jaric

Other Investigators: Anthony Machi

You are being asked to participate in a research study. This form tells you about the study including its purpose, what you will be asked to do if you decide to participate, and any risks and benefits of being in the study. Please read the information below and ask the research team questions about anything we have not made clear before you decide whether to participate. Your participation is voluntary and you can refuse to participate or withdraw at any time without penalty or loss of benefits to which you are otherwise entitled. If you decide to participate, you will be asked to sign this form and a copy will be given to you to keep for your reference.

WHAT IS THE PURPOSE OF THIS STUDY?

The purpose of this study is to examine how external loads change the force-velocity and power-velocity producing capabilities of humans during vertical jumping. We hope to use this information to develop a simple and routine test for the power producing capabilities of humans. This study also is part of the master’s thesis of Daniel Feeney

You are being asked to take part in this study because…

- You are a 18-26 year old male that is regularly active and have no history of leg injury in the past year.
• You would be excluded from volunteering in this study if you had any neurological conditions, recent injury, or are actively training for a sport.
• We expect to recruit 10- subjects

**WHAT WILL YOU BE ASKED TO DO?**

• During this study, you will be expected to first be testing on your maximal leg extension power with the use of a Kin- Kom device (isokinetic dynamometer). After that, you will practice jumping with a loaded vest. On the second visit to the lab, you will be jumping a total of 36- times with 9 different load conditions. You will be given 30 seconds between consecutive jumps and 2- minutes between jumps of different load.
• We will perform this study both in the University of Delaware human performance lab for the Kin- Kom as well as the STAR campus BADER treadmill lab. Two total sessions will take place and they each last about 1 to 1.5 hours.

<table>
<thead>
<tr>
<th>Visit 1</th>
<th>Visit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthropomorphic measurements</td>
<td>Warm up and stretching</td>
</tr>
<tr>
<td>Warm up and isokinetic leg extensor tests on Kin- Com (60 and 180 degrees/second)</td>
<td>1st series of 18 vertical jumps (3 at each load) followed by 10- minutes of rest</td>
</tr>
<tr>
<td>Familiarization with loaded vertical jumping</td>
<td>2nd series of 18 vertical jumps (3 at each load)</td>
</tr>
</tbody>
</table>

**WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?**

• The inherent risks for physical activity apply such as possible soreness for up to 48- hours after the trials.
• We will closely monitor you during the jumping procedure to ensure no physical harm occurs.
WHAT ARE THE POTENTIAL BENEFITS?

- There will not likely be a direct benefit to you for participation in this study, however after completion of the study, results will better our understanding of the leg muscles in vertical jumping and may provide insightful information about further training for force, power, and speed.

HOW WILL CONFIDENTIALITY BE MAINTAINED?

- We will maintain your confidentiality during this experiment as you will only be listed as a subject number in all data reporting measures.
- Paper records of trial numbers will be securely locked in the motor control lab and all electronic files will be kept confidential under a password protected computer.
- We will be recording your movement with the use of Cortex, a software that does not record any images of yourself, but rather movements of markers on you. There are no identifying parts of the recordings.
- Results from this study are expected to be reported at scientific conferences as well as in peer reviewed journals.

Your research records may be viewed by the University of Delaware Institutional Review Board, but the confidentiality of your records will be protected to the extent permitted by law.

WILL THERE BE ANY COSTS RELATED TO THE RESEARCH?

- There will be no direct costs to you, the subject, during this study.

WILL THERE BE ANY COMPENSATION FOR PARTICIPATION?

There is no compensation for completing this study.

WHAT IF YOU ARE INJURED DURING YOUR PARTICIPATION IN THE STUDY?

If you are injured during research procedures, you will be offered first aid at no cost to you. If you need additional medical treatment, the cost of this treatment will be your responsibility or that of your third-party payer (for example, your health insurance). By signing this document you are not waiving any rights that you may have if injury was the result of negligence of the university or its investigators.
DO YOU HAVE TO TAKE PART IN THIS STUDY?

Taking part in this research study is entirely voluntary. You do not have to participate in this research. If you choose to take part, you have the right to stop at any time. If you decide not to participate or if you decide to stop taking part in the research at a later date, there will be no penalty or loss of benefits to which you are otherwise entitled. Your refusal will not influence current or future relationships with the University of Delaware.

As a student, if you decide not to take part in this research, your choice will have no effect on your academic status or your grade in the class.

WHO SHOULD YOU CALL IF YOU HAVE QUESTIONS OR CONCERNS?

If you have any questions about this study, please contact the Principal Investigator, Daniel Feeney at 302-229-5641

Slobodan Jaric at 302-831-6174

If you have any questions or concerns about your rights as a research participant, you may contact the University of Delaware Institutional Review Board at 302-831-2137.

_________________________________
Signature of Participant

Date

Printed Name of Participant
Appendix B

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

(August 2002)

SHORT LAST 7 DAYS- Self Administered Format

For use with Young and Middle-aged Adults (15-69 years)

The International Physical Activity Questionnaires (IPAQ) comprises a set of 4 questionnaires. Long (5 activity domains asked independently) and short (4 generic items) versions for use by either telephone or self-administered methods are available. The purpose of the questionnaires is to provide common instruments that can be used to obtain internationally comparable data on health–related physical activity.

Background on IPAQ
The development of an international measure for physical activity started in Geneva in 1998 and was followed by extensive reliability and validity testing undertaken across 12 countries (14 sites) during 2000. The final results suggest that these measures have acceptable measurement properties for use in many settings and in different languages, and are suitable for national population-based prevalence studies of participation in physical activity.

Using IPAQ
Use of the IPAQ instruments for monitoring and research purposes is encouraged. It is recommended that no changes be made to the order or wording of the questions as this will affect the psychometric properties of the instruments.

Translation from English and Cultural Adaptation
Translation from English is supported to facilitate worldwide use of IPAQ. Information on the availability of IPAQ in different languages can be obtained at www.ipaq.ki.se. If a new translation is undertaken we highly recommend using the prescribed back translation methods available on the IPAQ website. If possible please consider making your translated version of IPAQ available to others by contributing it to the IPAQ website. Further details on translation and cultural adaptation can be downloaded from the website.
Data Entry and Coding
Attached to the response categories for each question are suggested variable names and valid ranges to assist in data management and interviewer training. We recommend that the actual response provided by each respondent is recorded. For example, “120 minutes” is recorded in the minutes response space. “Two hours” should be recorded as “2” in the hours column. A response of “one and a half hours” should be recorded as either “1” in hour column and “30” in minutes column.

Further Developments of IPAQ
International collaboration on IPAQ is on-going and an International Physical Activity Prevalence Study is in progress. For further information see the IPAQ website.

More Information

Short Last 7 Days IPAQ

READ: I am going to ask you about the time you spent being physically active in the last 7 days. Please answer each question even if you do not consider yourself to be an active person. Think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

READ: Now, think about all the vigorous activities which take hard physical effort that you did in the last 7 days. Vigorous activities make you breathe much harder than normal and may include heavy lifting, digging, aerobics, or fast bicycling. Think only about those physical activities that you did for at least 10 minutes at a time.

1. During the last 7 days, on how many days did you do vigorous physical activities?
   _____ Days per week [VDAY; Range 0-7, 8,9]

[Interviewer clarification: Think only about those physical activities that you do for at least 10 minutes at a time.]
[Interviewer note: If respondent answers zero, refuses or does not know, skip to Question 3]

2. How much time did you usually spend doing **vigorous** physical activities on one of those days?

   ___ ___ Hours per day \[VDHRS; Range: 0-16\]
   ___ ___ Minutes per day \[VDMIN; Range: 0-960, 998, 999\]
   998. Don't Know/Not Sure
   999. Refused

[Interviewer clarification: Think only about those physical activities you do for at least 10 minutes at a time.]

[ Interviewer probe: An average time for one of the days on which you do vigorous activity is being sought. If the respondent can't answer because the pattern of time spent varies widely from day to day, ask: "How much time in total would you spend over the last 7 days doing vigorous physical activities?"

   ___ ___ Hours per week \[VWHRS; Range: 0-112\]
   ___ ___ ___ Minutes per week \[VWMIN; Range: 0-6720, 9998, 9999\]
   9998. Don't Know/Not Sure
   9999. Refused

READ: Now think about activities which take **moderate physical effort** that you did in the last 7 days. Moderate physical activities make you breathe somewhat harder than normal and may include carrying light loads, bicycling at a regular pace, or doubles tennis. Do not include walking. Again, think about only those physical activities that you did for at least 10 minutes at a time.

3. During the last 7 days, on how many days did you do **moderate** physical activities?

   _____ Days per week \[MDAY; Range: 0-7, 8, 9\]
   8. Don't Know/Not Sure
   9. Refused

[Interviewer clarification: Think only about those physical activities that you do for at least 10 minutes at a time]
[Interviewer Note: If respondent answers zero, refuses or does not know, skip to Question 5]

4. How much time did you usually spend doing moderate physical activities on one of those days?
   ____ ____ Hours per day [MDHRS; Range: 0-16]
   ____ ____ Minutes per day [MDMIN; Range: 0-960, 998, 999]
   998. Don't Know/Not Sure
   999. Refused

[Interviewer clarification: Think only about those physical activities that you do for at least 10 minutes at a time.]

[Interviewer probe: An average time for one of the days on which you do moderate activity is being sought. If the respondent can't answer because the pattern of time spent varies widely from day to day, or includes time spent in multiple jobs, ask: “What is the total amount of time you spent over the last 7 days doing moderate physical activities?”
   ____ ____ ____ Hours per week [MWHRS; Range: 0-112]
   ____ ____ ____ Minutes per week [MWMIN; Range: 0-6720, 9998, 9999]
   9998. Don't Know/Not Sure
   9999. Refused

READ: Now think about the time you spent walking in the last 7 days. This includes at work and at home, walking to travel from place to place, and any other walking that you might do solely for recreation, sport, exercise, or leisure.

5. During the last 7 days, on how many days did you walk for at least 10 minutes at a time?
   ____ ____ Days per week [WDAY; Range: 0-7, 8, 9]
   8. Don't Know/Not Sure
   9. Refused

[Interviewer clarification: Think only about the walking that you do for at least 10 minutes at a time.]
6. How much time did you usually spend walking on one of those days?
   __ __ Hours per day  [WDHRS; Range: 0-16]
   __ __ __ Minutes per day  [WDMIN; Range: 0-960, 998, 999]

   998. Don't Know/Not Sure
   999. Refused

[Interviewer probe: An average time for one of the days on which you walk is being sought. If the respondent can't answer because the pattern of time spent varies widely from day to day, ask: “What is the total amount of time you spent walking over the last 7 days?”

   __ __ __ Hours per week  [WWHRS; Range: 0-112]
   __ __ __ __ Minutes per week  [WWMIN; Range: 0-6720, 9998, 9999]

   9998. Don't Know/Not Sure
   9999. Refused

READ: Now think about the time you spent sitting on week days during the last 7 days. Include time spent at work, at home, while doing course work, and during leisure time. This may include time spent sitting at a desk, visiting friends, reading or sitting or lying down to watch television.

7. During the last 7 days, how much time did you usually spend sitting on a week day?
   __ __ Hours per weekday  [SDHRS; 0-16]
   __ __ __ Minutes per weekday  [SDMIN; Range: 0-960, 998, 999]

   998. Don't Know/Not Sure
   999. Refused

[Interviewer clarification: Include time spent lying down (awake) as well as sitting]
**Interviewer probe:** An average time per day spent sitting is being sought. If the respondent can't answer because the pattern of time spent varies widely from day to day, ask: “What is the total amount of time you spent sitting last **Wednesday**?”

___ ___ Hours on Wednesday [SWHRS; Range 0-16]

___ ___ Minutes on Wednesday [SWMIN; Range: 0-960, 998, 999]

998. Don't Know/Not Sure