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**Kinesiological limits of vertical jump performance**

**Aragón-Vargas, Luis Fernando, Ph.D.**

**The University of Michigan, 1994**

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**KINESIOLOGICAL LIMITS OF VERTICAL JUMP PERFORMANCE**

**by**

**Luis Fernando Aragón-Vargas**

A dissertation submitted in partial fulfillment  
of the requirements for the degree of  
Doctor of Philosophy  
(Kinesiology)  
in The University of Michigan  
1994

**Doctoral Committee:**

**Assistant Professor M. Melissa Gross, Chair**  
**Professor Victor L. Katch**  
**Professor M. Anthony Schork**  
**Associate Professor Charles J. Worringham**



"Do you not know?  
Have you not heard?  
The LORD is the everlasting God,  
the Creator of the ends of the earth.  
He will not grow tired and weary,  
and increases the power of the weak.

Even youths grow tired and weary  
and young men stumble and fall;  
but those who hope in the LORD  
will renew their strength.

They will soar on wings like eagles;  
they will run and not grow weary,  
they will walk and not be faint."

(Is. 40:28-31)

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To Ana Mia, I love you with all my heart.

To Ana Victoria, I will be back.

To my Lord, who gives me strength, all glory be to your name.

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## CHAPTER I

### INTRODUCTION

Vertical jump performance (VJP) has been studied by researchers for decades, not only because of its importance for successful performance in sports such as basketball and volleyball, but also because it may be applied to understanding human motor control (Asmussen & Bonde-Petersen 1974, Bangerter 1968, Cavagna et al. 1972, Bobbert & van Ingen Schenau 1988, Eisenman 1978, Jensen & Phillips 1991, Pandy & Zajac 1991, van Ingen Schenau 1989). Traditionally, it was assumed that VJP depended heavily on muscle strength, and much of the early research on jumping focused on methods of strength training to improve jump performance. While there is consensus that lower limb muscular strength plays an important role in VJP, more recent work by Bobbert & van Ingen Schenau (1988, 1990), Hudson (1986), Pandy et al. (1990), Pandy & Zajac (1991), Robertson & Fleming (1987), van Soest et al. (1985), and Yamazaki et al. (1989), suggests that other aspects of the execution of a vertical jump are also relevant to performance. Unfortunately, these studies of vertical jumping have focused on similarities among good performers, and no comparisons have been made between good and bad jumpers to identify parameters associated with good but not with bad performance. Furthermore, little information has been provided about the plasticity of jumping performance and its determinants. In general, the factors affecting maximum VJP are not fully understood.

Leg muscular strength is significantly associated with VJP, but the relationship is only moderate. Eisenman (1978) reports a correlation of 0.47 between isometric knee strength and jump height. Genuario & Dolgener (1980) found that peak isokinetic

torques for several leg movements were poor predictors ( $r \approx 0.50$ ) of vertical jump height. The highest correlations have been reported by Podolsky et al. (1990), who developed multiple regression models to predict jump height in figure skating, based on isokinetic strength tests. They obtained a single correlation coefficient of 0.89 between knee extension isokinetic strength ( $240 \text{ degrees} \cdot \text{s}^{-1}$ ) and single axel jump height adjusted for body weight.

Improvements in vertical jump performance following strength training, however, are small. Typically, researchers have found improvements of 1.78 cm to 8.13 cm (Eisenman 1978). Smaller jump improvements have been reported after isometric training (0.76 cm -1.5%- McKethan & Mayhew 1974), while the larger gains are reported for isokinetic programs (4.93 cm, Blattner & Noble 1979) and plyometric training (5.50 and 7.30 cm, Brown et al. 1986), representing an improvement between 8 and 12%, relative to baseline performance. These relatively small gains are present even when leg muscular strength has increased considerably. For example, Eisenman (1978) found a poor correlation ( $r=0.19$ ,  $p>0.05$ ) between change in knee extension strength (improvement = 18.2%) and change in vertical jump performance (7.1%). Assuming that the muscle strength measures obtained in these studies were valid, and that the relevant muscle groups were trained (a reasonable assumption at least in the case of plyometric training), it becomes apparent that muscular strength may not be the most important factor in VJP.

VJP is affected by the presence or absence of the stretch-shortening cycle. Jump height is greater when humans are allowed to do a preparatory counter-movement than when the jump is performed from a fixed, stationary position (Asmussen & Bonde-Petersen 1974, Komi & Bosco 1978). This has been attributed to storage of elastic energy at the end of the eccentric (negative) phase of the movement, when muscles are forcibly stretched. This stored elastic energy is then utilized during the concentric (positive) phase of the jump (Cavagna 1977, Komi & Bosco 1978). Cavagna, Dusman &

Margaria (1968) have clearly shown a greater tension in the musculotendon unit at the onset of concentric action under these circumstances. Nevertheless, several authors have challenged the concept of elastic energy utilization as the sole explanation for higher jumps (see Asmussen & Bonde-Petersen 1974, Bobbert et al. 1987b, van Ingen Schenau 1984). Bosco et al. (1981, 1982) suggest that myoelectrical potentiation via the stretch reflex results in stronger contractions of the leg extensor muscles. Yamazaki, Suzuki & Mano (1989) showed that similar effects to those obtained in counter-movement jumps can be produced by static manipulations which result in increased musculotendon forces at the onset of concentric action (positive work) in the plantar flexors. Whatever the mechanism(s), the stretch-shortening cycle allows the neuromuscular system to produce a better jump. Its effects on VJP can be assessed from measures of peak negative impulse of the center of mass of the body, peak joint angular accelerations during the negative phase of the jump, and net joint torques at the time of joint reversals, which approximate the onset of concentric action of the muscles.

VJP is a multiarticular task and, as such, requires detailed analysis of the segmental motions. Although it has long been recognized that multiple segments are involved in vertical jumping (Luhtanen & Komi 1978), the relative importance of different body segment movements or muscle group actions is not resolved. Hubley & Wells (1983) concluded most of the work done during the jump was contributed by the knee, while Robertson & Fleming (1987) concluded the knee was the smallest contributor. In contrast, Fukashiro & Komi (1987) concluded that the hip was contributing most to total mechanical work done. Pandy & Zajac (1991) used forward dynamics in computer modelling, and looked directly at the contribution of muscles and energy content of body segments. They concluded that at the instant of take-off, 70% of the energy resides in the trunk, and challenged the previous investigators stating that energy flows proximally among segments during the jump, and not distally as had been widely accepted. In spite of these controversies, there is general agreement that all

modelled segments of the body (feet, shanks, thighs, and upper body), play an important role in maximum vertical jump performance.

Coordination of body segments may be a major factor determining VJP. The existence of a proximal-to-distal sequence of activation of muscle groups has been observed and explained in maximum VJP (Bobbert & van Ingen Schenau 1988, Hudson 1986, Pandy & Zajac 1991). Consistent with the EMG findings, a proximal-to-distal sequence of joint reversals (Bobbert & van Ingen Schenau 1988, Hudson 1986) has also been observed. Although sequential, the joint reversals and peak angular velocities are tightly coupled, occurring within 25 to 100 ms of each other (Hudson 1986, Jensen & Phillips 1991, van Ingen Schenau 1989). There is no empirical evidence on whether VJP actually varies with variations in timing and sequence of joint reversals, but a nearly simultaneous, proximal-to-distal occurrence of joint reversals seems to be desirable in order to optimize the "effective energy" (kinetic plus potential) of the body center of mass at take-off (Bobbert 1988).

In summary, existing studies provide a good theoretical basis for proposing a set of kinesiological factors relevant for VJP. Muscular strength of the lower limbs has traditionally been considered important. The actual execution of the jump seems to be very important as well. At a segmental level, the negative (eccentric) phase of the jump may have a significant effect on musculotendon forces at the onset of the positive phase, which in turn may affect VJP. During the positive phase, important execution characteristics may include dynamic (net joint torques, joint powers) as well as kinematic variables (timing of joint actions). From a whole-body perspective, average acceleration, time of propulsion, and total displacement of the center of mass during the positive phase may all be closely related to vertical jump performance. Finally, the vertical position and velocity of the body center of mass at the instant of take-off need to be considered as well. Since all of these factors are interrelated in a complex fashion, a sensible approach

to studying their relevance to vertical jump performance is using an analysis which integrates all of these factors, such as multiple regression analysis.

In the work that follows, the relative importance of a broad spectrum of kinesiological factors associated with VJP is assessed for the first time using multiple regression analysis. A theoretical model is presented which provides the basis for this regression analysis (see Figure 2.2). The model organizes the theoretically relevant kinesiological variables into different levels, to provide insight into the factors that limit performance. Specific hypotheses were formulated based on these hierarchical variables. The specific hypotheses are presented in Table 1.1. The percentages stated in hypotheses three, four, and five are proposed assuming that these models can do at least as well as other models reported in the literature, and assuming that the within-subject small performance differences will result in less powerful models.

Two separate papers are presented. The purpose of the first paper (Chapter II) is to identify the differences in kinesiological factors associated with differences in VJP among subjects representing a wide range of jumping abilities. The study will investigate what distinguishes a good jumper from a poor one. There is a possibility that large between-subject differences in strength, weight, or height, or even variables that were not included in the first paper, may obscure the relationship between some execution variables and VJP. The second paper (Chapter III) uses a single-subject research design to explore this possibility, showing the execution variables that vary with changes in VJP given the physiological and anthropometric characteristics of a particular subject. This study will investigate what is the motor control strategy used by individuals to maximize the height of the jump. The results from both studies are compared and discussed in Chapter IV, identifying the probable critical factors for VJP. Together, the studies provide a sound basis for future investigation on how to improve vertical jump performance, and add to the body of knowledge on human motor control strategies for maximum performance.

**Table 1.1. Specific hypotheses.****Chapter II: Differences among subjects.**

1. The vertical take-off velocity of the body center of mass (BCOM) is able to explain more of the variation in vertical jump performance (VJP) among subjects than the vertical position of the body center of mass at take-off.
2. The ankle joint angle at take-off is able to account for more of the between-subjects variation in the take-off net vertical position of BCOM than either the knee or the hip joint angles at take-off.
3. At least 80% of the between-subjects variation in vertical take-off velocity of BCOM can be accounted for by a statistical model which includes, as predictors, body mass, body height, and whole-body kinematics and dynamics.
4. At least 64% of the between-subjects variation in VJP can be accounted for by a statistical model that includes, as predictors, body mass, body height, and whole-body kinematics and dynamics.
5. At least 80% of the between-subjects variation in VJP can be accounted for by a statistical model that includes muscular strength of the lower limbs and segmental kinematics and dynamics of the jump.
6. Muscular strength of the lower limbs and segmental dynamics are able to explain more of the between-subjects variation in vertical take-off velocity than segmental kinematics of the execution of the jump.
7. Segmental kinematics are able to explain more of the between-subjects variation in the net vertical position of BCOM than muscular strength of the lower limbs and segmental dynamics of the execution of the jump.

**Chapter III: Within-subject differences.**

1. The vertical take-off velocity of the body center of mass (BCOM) is able to explain more of the within-subjects variation in vertical jump performance (VJP) than the vertical position of the body center of mass at take-off.
2. The ankle joint angle at take-off is able to account for more of the within-subjects variation in the take-off net vertical position of BCOM than either the knee or the hip joint angles at take-off.
3. At least 50% of the within-subjects variation in vertical take-off velocity of BCOM can be accounted for by a statistical model which includes whole-body kinematics and dynamics as predictors.
4. At least 40% of the within-subjects variation in VJP can be accounted for by a statistical model that includes whole-body kinematics and dynamics as predictors.
5. At least 50% of the within-subjects variation in VJP can be accounted for by a statistical model that includes segmental kinematics and dynamics of the jump.
6. Segmental dynamics are able to explain more of the within-subjects variation in vertical take-off velocity than segmental kinematics of the execution of the jump.
7. Segmental kinematics are able to explain more of the within-subjects variation in the net vertical position of BCOM than segmental dynamics of the execution of the jump.

**CHAPTER II**  
**KINESIOLOGICAL LIMITS OF VERTICAL JUMP PERFORMANCE:**  
**DIFFERENCES AMONG INDIVIDUALS**

**Glossary of Terms**

- AMECHP: Average mechanical power of the whole body.*
- AMP: Amplitude of the movement.*
- AVA: Average vertical acceleration.*
- BCOMNET: Net vertical position of the body center of mass at take-off.*
- DISTAPRO: Distal-to-proximal sequence of the maximum velocity differences between proximal and distal joints for each segment.*
- DISTOPRO: Distal-to-proximal sequence of the joint reversals.*
- HEIGHT: Body height.*
- j: Denotes a joint. ANK is ankles, KNE is knees, and HIP is hips.*
- jACCPK: Peak joint acceleration during the negative phase.*
- jANGTO: Joint angle at take-off.*
- jEXTIS: Joint extension isometric strength.*
- jFLXIS: Joint flexion isometric strength.*
- jMMAX: Maximum net joint torque.*
- jMREV: Net joint torque at the time of joint reversal.*
- jPFXIS: Joint plantar flexion isometric strength.*
- jPWRMAX: Peak joint power.*
- JREVDIF: Time difference between first and last joint reversals.*
- JUMP2: Jump height calculated from BCOMNET and TOVEL.*
- MMTDIFF: Time difference between the first and last maximal joint torques.*
- NEGIMMAX: Peak negative impulse of the body center of mass.*
- PEAKPWR: Peak mechanical power of the whole body.*
- PRODISTA: Proximal-to-distal sequence of the maximum velocity differences between proximal and distal joints for each segment.*
- PROTODIS: Proximal-to-distal sequence of the joint reversals.*
- TOVEL: Vertical take-off velocity of the body center of mass.*
- TPROP: Time of propulsion.*
- VJP: Vertical jump performance.*
- WEIGHT: Body weight.*

## Introduction

Vertical jump performance (VJP) has been studied by researchers for decades. Early interest was related to jumping in sports such as basketball and volleyball. More recently, as a simple task where maximum performance is clearly and objectively defined, the vertical jump has been applied to understanding human motor control of a multiarticular movement. One major practical question, however, remains the same: which kinesiological factors are critical for vertical jump performance? There has been a tendency among coaches and trainers to focus on lower limb muscular strength training as a means to improve VJP, but it seems that other factors can affect vertical jump performance as well.

Early research on the vertical jump focused on the role of muscular strength and the effects of various methods of strength training on VJP (Ball 1964, Bangerter 1968, Blattner & Noble 1979, Brown et al. 1986, Eisenman 1978, Genuario & Dolgener 1980, McKethan & Mayhew 1974). In general, these studies report a moderate association of muscular strength and VJP ( $r=0.50$ , Genuario and Dolgener 1980), and relatively small improvements of 8-12% in jump performance with strength training (Blattner & Noble 1979, Brown et al. 1986).

There was also some early interest in storage and utilization of elastic energy and its effects on VJP (Asmussen & Bonde-Petersen 1974, Komi & Bosco 1978). These papers and others on the utilization of stored elastic energy in skeletal muscle (Cavagna, Dusman & Margaria 1968), on motor control of the locust jump (Heitler & Burrows 1977a,b), and on various manipulations of the vertical jump (Yamazaki, Suzuki & Mano 1989), suggest that high musculotendon forces at the onset of the concentric action enhance jumping performance. Researchers have also studied the relative contributions of joint or segment actions to the jump (Fukashiro & Komi 1987, Hubble & Wells 1983, Luhtanen & Komi 1978, Pandy & Zajac 1991, Robertson & Fleming 1987), the role of

biarticular muscles in vertical jumping (Bobbert & van Ingen Schenau 1990, Pandy & Zajac 1991, van Ingen Schenau et al. 1985), and specific motor control issues such as coordination of the segmental actions (Bobbert & van Ingen Schenau 1988, Hudson 1986, Jensen & Phillips 1991, Pandy & Zajac 1991).

The work of these scientists has allowed a considerable refinement of the biomechanical techniques and models used to study VJP, and has identified several variables which are common to maximum vertical jump performance, such as high musculotendon forces and joint torques at the onset of the positive phase; high joint powers, especially towards the time of take-off; close occurrence of a proximal-to-distal sequence of activation of muscle groups, reflected in the sequence of joint reversals; and an optimization of the vertical position of the body center of mass at the instant of take-off. Most of these studies, however, have focused on similarities among good performers, and few comparisons have been made between good and bad jumpers. Identifying the variables associated with good but not with bad performance is necessary to determine which factors are most important for VJP.

Since most of the factors proposed as relevant to VJP are interrelated in a complex fashion, a sensible approach to their study is the utilization of multiple regression analysis techniques. Multiple regression has been used previously in the study of VJP (Dowling & Vamos 1993, Hay et al. 1978, Jaric et al. 1989, Podolsky et al. 1990), but the variables studied were somewhat limited. The papers by Jaric and colleagues and Podolsky and colleagues focused on muscular strength measures. Dowling & Vamos restricted their study to whole-body mechanics and timing issues. The study by Hay and colleagues focused on average joint torques at particular intervals using a rather complex (11 segment) model. They did not include any of the coordination-related predictor variables that have been identified more recently. The present study collects those variables proposed in the literature as potential predictors, organizes them according to a theoretical model, and studies them in a group of men with a wide range of jumping

abilities, in an attempt to identify the kinesiological factors which are critical for vertical jump performance.

## **Methods**

### **Data acquisition**

52 normal, physically active male college students each performed five maximal vertical jumps, starting from the position of their choice, with their hands on their hips (arms akimbo). Informed consent was obtained from all subjects in accordance with the policy statement of the University of Michigan. They completed three practice jumps before data collection, and were required to wait for one minute after each trial. Subjects performed the jumps barefooted, wearing only a swimsuit or pair of shorts. Five reflective markers were placed on the right side of the body, on the glenohumeral joint (SHOulder), the greater trochanter (HIP), the lateral condyle of the femur (KNEe), the lateral malleolus (ANKle), and the fifth metatarsal (TOE). The best jump of each subject was selected for analysis, using the VJP criterion (maximum jump height) as defined below in equation #7.

Ground reaction forces and moments of force were collected with a Bertec force plate (model 4060A), sampled at 300 Hz. A video-based (60 Hz), real-time, 3-D motion analysis system (Motion Analysis Corp.) was used to collect and process kinematic data. Kinematic data were filtered with a low-pass, fourth-order Butterworth filter with an effective cutoff frequency of 8 Hz.

Strength of the lower body was tested isometrically at the hip, knee, and ankle joints, at a separate session, using a Biodex machine. Standard Biodex procedures were used for the knee and ankle joint tests<sup>1</sup>. The hip joint test was adapted from the procedures described in the Cybex II operation manual<sup>2</sup>. Subjects had a brief warm-up period and three practice trials prior to each test. They were instructed to exert maximum

force for a period of five seconds, with 15 seconds of rest between trials. The maximum torque averaged over three trials was obtained. Joint strength was defined as the average of both the right and left joints. Joint angles during testing were standardized according to Table 2.1.

**Table 2.1.** Joint angles used for isometric strength tests.

	Hip	Knee	Ankle
Hip extension <sup>a</sup>	90°	90°	-----
Hip flexion <sup>a</sup>	90°	90°	-----
Knee extension <sup>b</sup>	120°	120°	-----
Knee flexion <sup>b</sup>	120°	120°	-----
Ankle plantar flexion <sup>c</sup>	110°	140°	80°

(a) Based on Nemeth et al. (1983) and Waters et al. (1974).

(b) From Lindahl et al. (1969) and Scudder (1980).

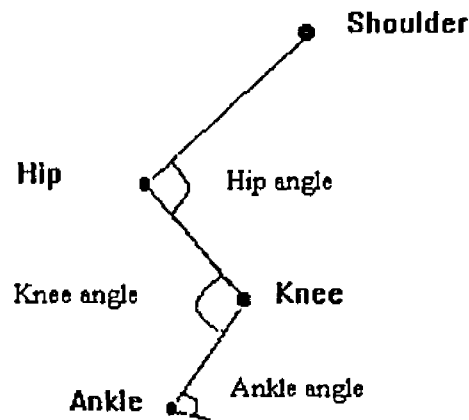
(c) Based on Fugl-Meyer et al. (1980) and Sale et al. (1982).

Basic anthropometric data were obtained using standard sliding calipers, tape measures, and the force platform. Body mass and body height were measured according to Lohman et al. (1988). Thigh length, midthigh circumference, shank length, calf circumference, malleolus width, malleolus height, and foot length were obtained according to Vaughan et al. (1992). These data were used for the calculation of segmental center of mass and moment of inertia values (see below).

### **Data analysis**

The body was modeled as a planar, rigid-body system consisting of four segments linked by frictionless, hinge joints (Figure 2.1). Although the effects of an arm swing on VJP have been shown to be relevant (Jensen 1990), the utility of a four segment model for the study of vertical jumping is well documented (Bobbert et al. 1987a, 1987b,

Bobbert & van Ingen Schenau 1988, Pandy et al. 1990, Pandy & Zajac 1991, Zajac et al. 1981), and allows a more specific focus on the lower limb muscle actions.



**Figure 2.1. Biomechanical model.** Segments ( $i = 1$  to 4) are defined by the markers: segment 1, head, arms and trunk (HAT), from shoulder to hip; segment 2, thighs (THI), from hip to knee; segment 3, shanks (SHA), from knee to ankle, and segment 4, feet (FET), from ankle to toe.

Segmental ( $COM_i$ ), and whole body (BCOM) center of mass positions in the horizontal ( $x$ ) and vertical ( $z$ ) axes were calculated according to Vaughan et al. (1992). The procedure used for calculating the HAT parameters was based on data from Clauser et al. (1969) and Hinrichs (1990)<sup>3</sup>. Segmental moments of inertia about the center of mass were calculated according to Vaughan et al. (1992), using their formulae for the sagittal plane.

Angular velocities and accelerations were obtained by differentiating joint angular displacement data, using finite differences. Joint angles are defined in Figure 2.1. According to this convention, when a joint is flexing the angular velocity is negative; it is positive when the joint extends.

Kinematic analysis of the body center of mass included the time of propulsion, average vertical acceleration, and amplitude of the movement. Time of propulsion was defined as:

$$t_{prop} = t_{t.o.} - t_{low} \quad (1)$$

where  $t_{low}$  is the instant when BCOM reaches its lowest point during counter-movement, and  $t_{t.o.}$  is the time of take-off (when  $F_z$  falls below 3.0 N, or less than 0.005% of body weight).

Average vertical acceleration of BCOM was calculated as:

$$AVA = \dot{z}_{BCOM} / t_{prop} \quad (2)$$

Amplitude of the movement was defined as the center of mass vertical excursion normalized for body height, to represent the extent to which each subject used his available range of motion. This was calculated according to:

$$AMP = \left( \frac{z_{takeoff\ BCOM} - z_{low\ BCOM}}{body.height} \right) * 100 \quad (3)$$

Kinematic and kinetic data were used to obtain the instantaneous net joint torques using Newtonian equations of motion (Winter, 1990)<sup>4</sup>. Joint extending torques are presented as positive and joint flexing torques as negative.

Mechanical power was calculated for the whole body, as well as for individual joints. Whole-body average mechanical power during propulsion was derived from the change in potential energy of the whole body, according to:

$$AMECHP = \frac{mg(z_{peak\ BCOM} - z_{low\ BCOM})}{t_{prop}} \quad (4)$$

where  $m$  is body mass, and  $g = 9.81 \text{ m} * \text{s}^{-1}$ . Peak mechanical power (PEAKPWR) was obtained from the instantaneous mechanical power of the whole body, calculated according to Dowling and Vamos (1993):

$$\dot{W} = F_z * \dot{z}_{BCOM} \quad (5)$$

Finally, instantaneous joint powers were calculated according to Robertson & Winter (1980):

$$\dot{W}_j = M_j * \omega_j \quad (6)$$

where  $\dot{W}_j$  is the power for joint  $j$  at each point in time,  $M_j$  is the instantaneous torque for joint  $j$ , and  $\omega_j$  is the instantaneous angular velocity at joint  $j$ .

The performance criterion was vertical jump performance (VJP), defined as the peak vertical position of the center of body mass during flight, minus the center of body mass height while standing:

$$VJP = z_{peak} BCOM - z_{standing} BCOM \quad (7)$$

Equivalently, jump height can be calculated from the vertical velocity and net position of the whole body center of mass at take-off:

$$JUMP2 = \left[ (\dot{z}_{take-off} BCOM)^2 * (2g)^{-1} \right] + z_{takeoff} BCOM - z_{standing} BCOM \quad (8)$$

Vertical take-off velocity (TOVEL) was obtained from

$$\dot{z}BCOM = \frac{\int_{t_0}^{t_a} F_{zp} dt}{m} \quad (9)$$

where  $F_{zp}$  is the propulsive force, obtained by subtracting body weight from the vertical ground reaction force, and  $t_0$  is the beginning of data collection.

### Potential predictor variables

Figure 2.2 shows a theoretical model of the relevant factors in vertical jump performance. This model recognizes that variables are highly interrelated, while allowing for different levels of analysis.

The first level of analysis is concerned with a functional relation: the vertical position and vertical take-off velocity of the body center of mass define VJP. The second level of analysis deals with the variables that contribute more directly to the vertical

position of the body center of mass at take-off and vertical take-off velocity. These include the joint angles at take-off, and the whole-body kinematics and dynamics of the jump, respectively. The third level of analysis includes the segmental kinematics and dynamics of the jump. Potential predictor variables related to whole-body and segmental mechanics of the execution of the jump are listed in Table 2.2.

A fourth level of analysis should include the skeletal muscle characteristics and anthropometric characteristics of each individual. The segmental dynamics and kinematics of the jump are the result of how the nervous system makes use of these characteristics to maximize performance. This study deals only with one aspect of this fourth level of analysis which has been traditionally evaluated: muscular strength of the hip flexors and extensors, knee flexors and extensors, and ankle plantar flexors. Finally, two general characteristics are also included as potential predictors: body weight and height.

**Table 2.2.** List of level II and III predictors of VJP.

Whole-body kinematics and dynamics of the jump (II-B)	Segmental kinematics of the jump (III-A)	Segmental dynamics of the jump (III-B)
Average vertical acceleration (AVA)	Relative timing of joint reversals (PROTODIS)	Peak net joint torques (jMMAX)
Time of propulsion (TPROP)	Time difference between first and last peak net joint torques (MMTDIFF)	Net joint torques at time of joint reversals (JMREV)
Amplitude of the movement (AMP)	Relative timing of the peak velocity differences between proximal and distal joints for each segment (PRODISTA)	Peak joint powers (jPWRMAX)
Average mechanical power. (AMECHP)	Peak joint angular accelerations during the negative phase (jACCPK)	
Peak mechanical power (PEAKPWR)		
Peak negative impulse (NEGIMMAX)		

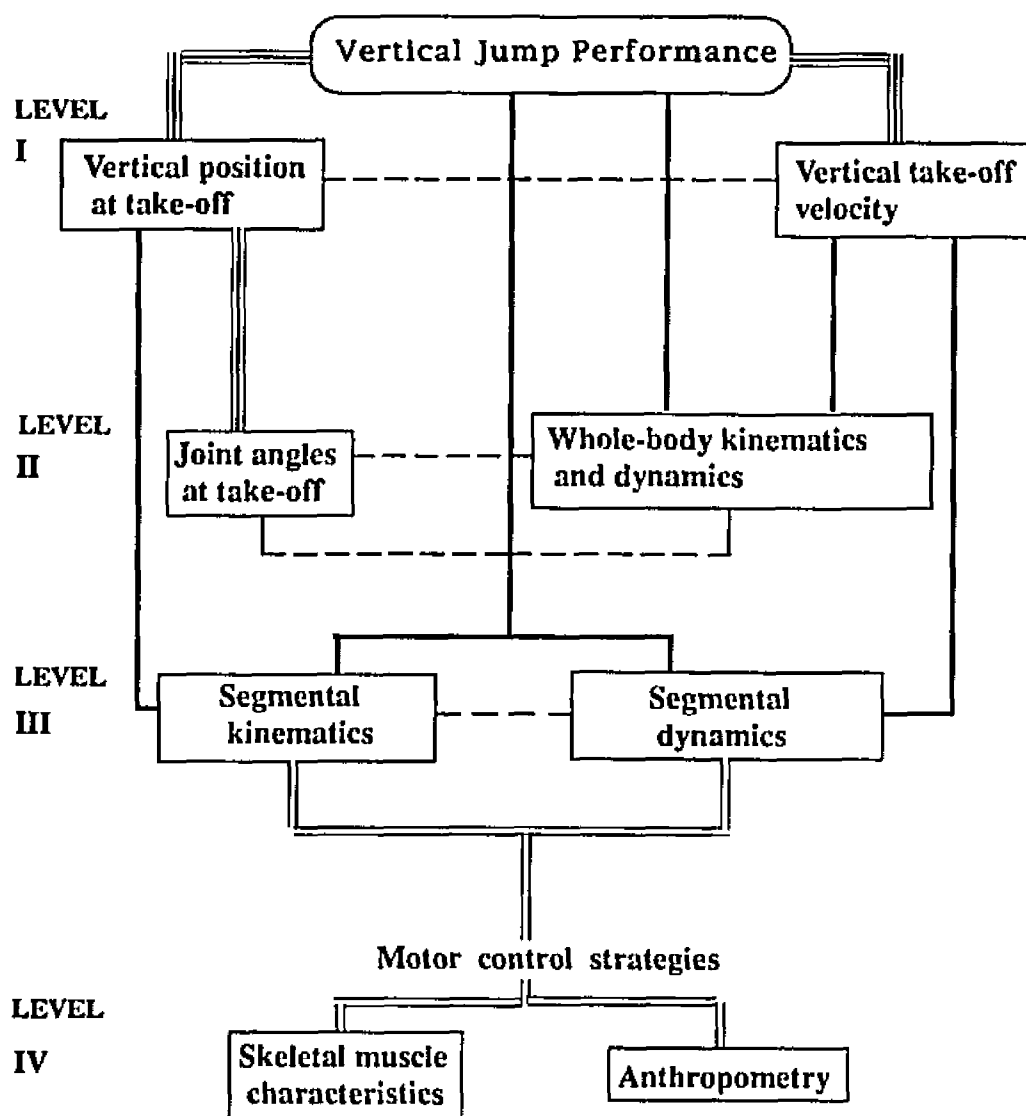


Figure 2.2. Theoretical model of vertical jump performance. Triple solid lines denote functional relations. Solid lines indicate the statistical relationships under study. Dotted lines recognize other interrelationships.

Two variables from Table 2.2 need further explanation. Peak negative impulse was calculated from the peak downward velocity of the body center of mass:

$$NEGIMMAX = m(\dot{z}_{\min}BCOM) \quad (10)$$

Velocity differences between proximal and distal joints for each segment (see Bobbert & van Ingen Schenau 1988) were calculated from the first derivative of vertical joint displacements, according to

$$Vdiff_i = (\dot{z}_{prox} - \dot{z}_{dist})_i \quad (11)$$

### Statistical analysis

Multiple regression analysis techniques were applied at each level of the model in Figure 2.2 to identify the major predictor variables. The basic model used was the general linear model:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_{p-1} x_{p-1} + E_j$$

where  $y$ , the dependent variable, is normally distributed;  $x_i$  is the  $i^{th}$  predictor,  $p-1$  is the number of predictors in the model,  $\beta_0$  is the intercept, and  $E_j$  are the error terms, which are independent and normally distributed. Descriptive statistics were used to verify that the basic assumption of normality of the dependent variables was met, and to investigate whether there was a reasonable variability of both dependent and predictor variables.

For each level of analysis, several statistical models were developed, using "all possible subsets" and "stepwise" regression techniques, and compared. Selection of the "best" models was made according to commonly used criteria, i.e., Mallows's  $C_p$  ( $C_p \cong p$ ), and  $R_a^2$  (highest adjusted r-squared values). The adjusted r-squared takes into account how many predictors are included in the model, since additional variables will usually improve r-squared but at the expense of complicating the model. Interactive stepwise regression was used to verify the significance and the relative importance of each predictor in the models. Since the purpose of this study was to identify the relevant predictors and not necessarily to build the most accurate model possible, selection of

several different models is a reasonable approach. These models were refined using residual analysis techniques, to check for the omission of important variables or the need for interaction terms or a curvilinear function. The presence of outliers was determined using leverage and studentized deleted residuals; their influence was assessed using Cook's D. Finally, the aptness of each model in terms of the normality of  $E_j$  was evaluated using normal probability plots.

## Results

General characteristics of the subjects are presented in Table 2.3. Tables 2.4 and 2.5 list the jump execution results. Average body weight (74.3 kg) was slightly above the U.S. population average for a body height of 1.78 m (71.8 kg) (Metropolitan Insurance Tables, 1959). Jump heights (VJP) ranged from 0.372 m to 0.663 m (mean = 0.520 m), and had a coefficient of variation of 13.4%. This average jump height is higher than reported in the literature for male college students jumping without an arm swing (i.e., 0.49 m, Brown et al. 1986, 0.42 m, Bosco & Komi 1979), but is lower than reported for trained basketball players (0.55 m, Brown et al. 1986) or trained volleyball players (0.54 m, Bobbert et al. 1987a). Of special relevance to the present study is the fact that the group represents a wide range of jumping abilities and physical activity levels. At the higher end of physical activity, seven subjects were members of the university's volleyball club, four were active in strength-related sports (college wrestling, recreational body building, and professional baseball), and two were endurance athletes (rowing, cross-country running). At the lower end were about 20 subjects who were only occasionally active in recreational basketball, jogging, or weight lifting. The majority of the subjects were kinesiology students at the local university.

Both VJP and take-off velocity (TOVEL) were normally distributed, but the net position of BCOM at take-off (BCOMNET) was positively skewed. The latter was

transformed (base 10 logarithm) before completing the analyses. Variability was higher for BCOMNET (C.V. = 18.9%) than for TOVEL (C.V. = 9.3%). Average values reported in Table 2.4 are reasonable when compared to those reported in other studies (Bobbert et al. 1987a, Bobbert & van Ingen Schenau 1988, Hudson 1986). Most subjects chose to perform a "counter-movement jump" (Asmussen & Bonde-Petersen 1974); the few that tried to do a "squat jump" actually used a small counter-movement.

Figure 2.3 shows representative curves of joint angles, joint angular velocities, net joint torques, and joint powers. The curves were obtained from one subject with an average VJP (0.537 m); other average jumpers (within 0.25 S.D. of the average,  $n = 11$ ) showed similar curves. These curves are comparable to those reported by Bobbert & van Ingen Schenau (1988). This subject shows a hip-ankle-knee sequence of joint reversals, a common pattern (21 out of 28) among subjects in the "other" category.

**Table 2.3.** Subject characteristics,  $n = 52$ .

Variable [variable name] (units)	Mean	Standard deviation	C.V. (%)
Age [AGE] (years)	20.2	2.1	10.4
Weight [WEIGHT] (kg)	74.27	8.65	11.6
Height [HEIGHT] (m)	1.79	0.06	3.4
Hip extension strength [HIPEXTIS] (N m)	160.46	34.55	21.5
Hip flexion strength [HIPFLXIS] (N m)	101.57	18.79	18.5
Knee extension strength [KNEEXTIS] (N m)	230.03	43.90	19.1
Knee flexion strength [KNEFLXIS] (N m)	121.05	24.20	20.0
Ankle plnt. flexion strength [ANKPFXIS] (N m)	130.66	19.91	15.2

**Table 2.4.** Jump execution characteristics, n = 52.

Variable name (units)	Mean	Std. deviation	C.V.(%)
VJP (m)	0.520	0.070	13.4
TOVEL (m * s <sup>-1</sup> )	2.651	0.246	9.3
BCOMNET (m)	0.144	0.027	18.9
HIPANGTO (rad)	3.01	0.09	3.0
KNEANGTO (rad)	3.08	0.09	2.9
ANKANGTO (rad)	2.52	0.10	4.2
TPROP (s)	0.316	0.062	19.6
AVA (m * s <sup>-2</sup> )	8.74	2.04	23.3
AMP (% body height)	31.33	5.44	17.4
AMECHP (W)	2212.9	455.1	20.6
PEAKPWR (W)	3863.2	687.7	17.8
NEGIMMAX (kg * m * s <sup>-1</sup> )	-87.8	36.6	41.7
HIPACCPK (rad * s <sup>-2</sup> )	56.79	17.44	30.7
KNEACCPK (rad * s <sup>-2</sup> )	34.66	15.31	44.2
ANKACCPK (rad * s <sup>-2</sup> )	52.07	41.66	80.0
MMTDIFF (s)	0.158	0.093	58.8
JREVTDIF (s)	0.113	0.077	68.6
HIPMMAX (N m)	295.51	74.26	25.1
KNEMMAX (N m)	220.84	77.54	35.1
ANKMMAX (N m)	244.80	48.25	19.7
HIPMREV (N m)	280.32	86.46	30.8
KNEMREV (N m)	206.07	80.44	39.0
ANKMREV (N m)	215.32	64.24	29.8
HIPPWRMAX (W)	1203.7	341.9	28.4
KNEPWRMAX (W)	1487.5	447.4	30.1
ANKPWRMAX (W)	1916.5	558.6	29.1

**Table 2.5.** Jump execution characteristics: sequence variables (n = 52).

Variable name	Frequency
PROTODIS	23
DISTOPRO	1
Other sequences of joint reversals	28
PRODISTA	42
DISTAPRO	0
Other sequences of peak velocity differences	10

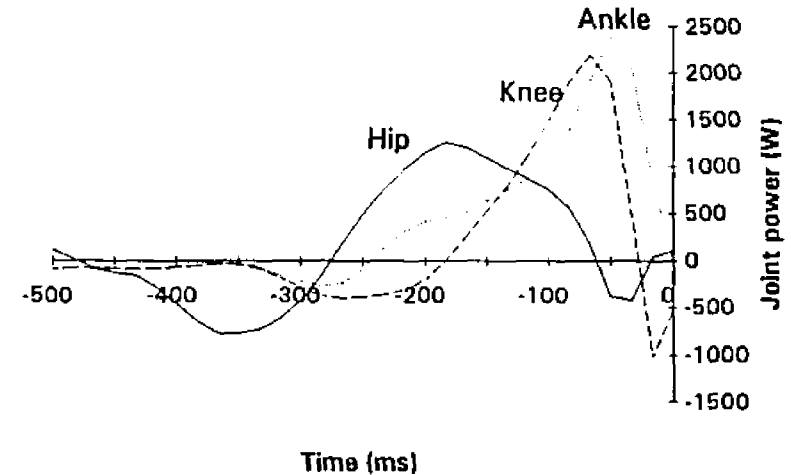
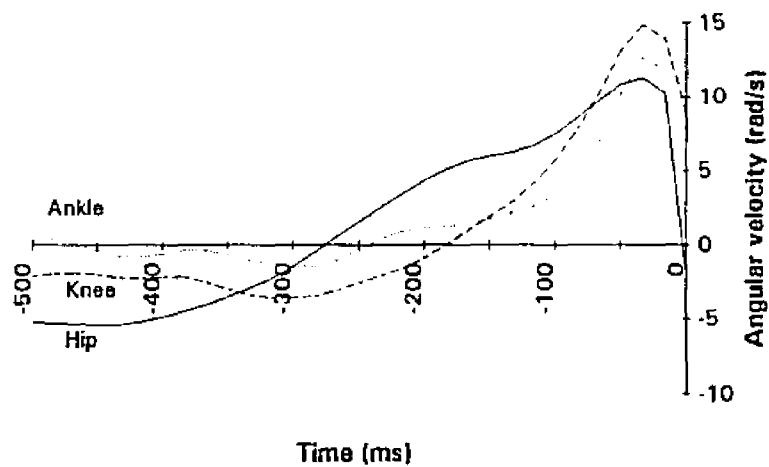
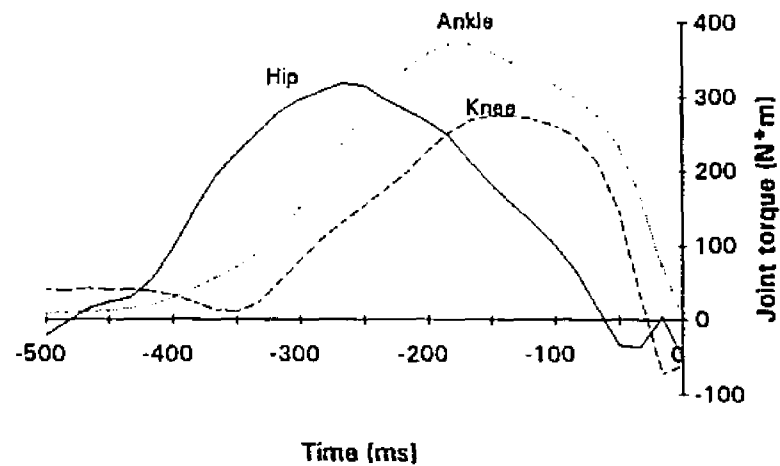
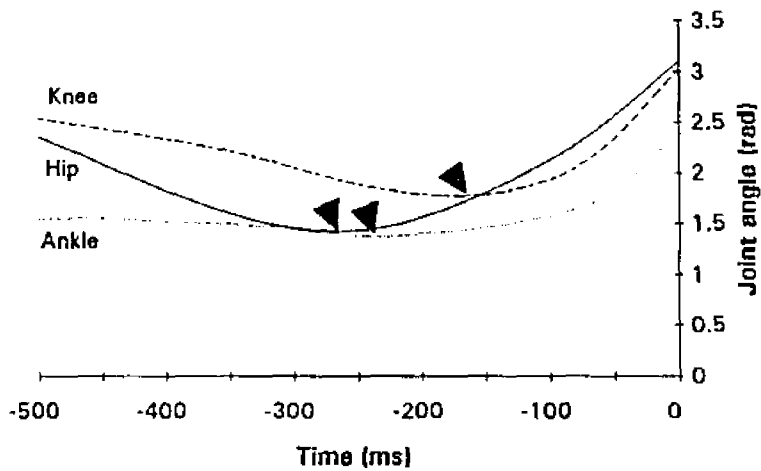


Figure 2.3. Joint kinematics and dynamics for a maximum vertical jump, subject db43t01. This is a representative subject with an average maximum vertical jump (0.537 m). Time = 0 represents the instant of take-off. Arrows in top left figure show the instant of joint reversal.

Table 2.6 shows a summary of the "best" prediction models developed for the dependent variables, organized by levels of analysis. When possible, three multivariate models are included at each level. Best single predictors are also included at each level. Both  $R^2$  and  $R_a^2$  values are reported, since each could point to a different model as the best one. Within each model, variables are presented in order of importance, according to their partial correlation coefficients. Several models not included in this table may have been reasonably good, but not good enough to be among the best. Table 2.6 includes information about how many significant models were not included in the table and what their best  $R^2$  values were. In addition, when a variable is discussed as not being relevant, additional information is provided about whether it was a significant predictor in any of the absent models<sup>5</sup>.

At level one, take-off velocity (TOVEL) is a much more powerful predictor of VJP than the position of BCOM at take-off (BCOMNET): the partial coefficients of determination when the other variable was already in the model were 0.937 for TOVEL and 0.256 for BCOMNET (total  $R^2 = 0.95$ ). Level two models show that it is possible to account for about 91% of the variation in TOVEL and 89% of the variation in VJP, using whole-body kinematics and dynamics of the jump. The two best single predictors of both dependent variables are peak mechanical power and average mechanical power.

Models at levels three and four show smaller coefficients of determination. The best prediction models for VJP have a large number of predictors, all of which had a significant effect on VJP ( $p < .05$ ). The three best models include peak hip power (HIPWRMAX), knee extension strength (KNEEXTIS), and a hip torque variable (HIPMMAX or HIPMREV), and account for about 60% of the variation in VJP. Peak knee power (KNEPWRMAX) is also an important predictor, while ankle torque, power, or strength are not as relevant. Best single predictors of VJP at these levels are peak hip power (HIPWRMAX) and torque (HIPMMAX). The best models using segmental

kinematics as predictors (models 21 & 24) are not as powerful as those using segmental dynamics (20,22,23,25) for predicting TOVEL and BCOMNET.

**Table 2.6.** "Best" prediction models at each level of analysis. All models, except when noted, were significant at  $p < .0005$ .

Prediction model for VJP	R <sup>2</sup>	R <sub>a</sub> <sup>2</sup>
<b>LEVEL I</b>		
1) VJP = k + tovel + bcomnet	.95	.94
2) VJP = k + tovel	.93	.93
<b>LEVEL II</b>		
3) BCOMNET = k + ankancto + hipangto	.32	.29
4) BCOMNET = k + kneangto	.24	.23
5) TOVEL = k - weight + peakpwr + amp + amechp	.91	.90
6) TOVEL = k + peakpwr - weight + amp + ava	.91	.90
7) TOVEL = k + peakpwr - weight + amp - tprop <sup>a</sup>	.91	.90
8) TOVEL = k + peakpwr	.52	.51
9) TOVEL = k + amechp	.44	.42
10) VJP = k - weight - ava + amechp + peakpwr	.89	.88
11) VJP = k - weight + amp + peakpwr + amechp	.88	.87
12) VJP = k + peakpwr - weight <sup>b</sup>	.72	.70
13) VJP = k + peakpwr	.46	.45
14) VJP = k + amechp	.43	.42
<b>LEVELS III and IV</b>		
15) VJP = k + hippwrmax + hipaccpk + kneextis - kneflxis - hipmrev + knepwrmax	.61	.56
16) VJP = k + hippwrmax + kneextis + knepwrmax + hipaccpk - kneflxis - hipmmax	.61	.56
17) VJP = k + hippwrmax - hipmrev + kneaccpk + hipaccpk + kneextis <sup>c</sup>	.59	.55
18) VJP = k + hippwrmax	.44	.43
19) VJP = k + hipmmax	.28	.26
20) TOVEL = k + hippwrmax + knepwrmax	.48	.46
21) TOVEL = k + hipaccpk <sup>d</sup>	.21	.19
22) TOVEL = k + hippwrmax	.43	.42
23) BCOMNET = k + ankpfxis + hippwrmax <sup>e</sup>	.30	.27
24) BCOMNET = k + hipaccpk <sup>f</sup>	.07	.05
25) BCOMNET = k + ankpfxis	.25	.23

a) Other models not included ( $n > 10$ ) were statistically significant, with  $R^2 = 0.89$  and lower.

b) Other models not included ( $n > 10$ ) were statistically significant, with  $R^2 = 0.87$  and lower. This particular model was included to illustrate the effect of these two variables alone.

c) Other models not included ( $n = 3$ ) were statistically significant, with  $R^2 = 0.51$  and lower.

d)  $p = .001$

e) Hippwrmax is borderline not-significant in this model ( $p = 0.05$ ).

f)  $p = .063$

## Discussion

This study shows how vertical jump performance can be predicted with different degrees of success, depending on the type of predictor variables used. Regarding level I, it has been shown that both TOVEL and BCOMNET are significant predictors of VJP. This is in good agreement with Bobbert & van Ingen Schenau (1988), who stated that the optimization of VJP involves both optimization of TOVEL and BCOMNET. It is possible that some subjects' strategies would favor one in detriment of the other, but subjects with a higher take-off velocity did not seem to achieve it at the expense of BCOM position at take-off (or vice versa); the correlation between TOVEL and BCOMNET was .247 ( $p = .078$ ), indicating a non-significant tendency for subjects with a higher TOVEL to show a higher BCOMNET as well. These results, together with the high predictive power of TOVEL, suggest that little information is added by studying the BCOMNET part of the vertical jump performance equation, at least when making between-subject comparisons.

Joint angles at take-off were significant but poor predictors of BCOMNET. Bobbert & van Ingen Schenau (1988) have proposed that a greater ankle angle at take-off may distinguish those jumpers who leave the ground with a higher BCOM position. The present data show that ANKANGTO was a significant predictor of BCOMNET ( $p = .001$ ), but could only account for about 21% of the variation in BCOMNET. KNEANGTO had a similar predictive ability (24%). Because joint angles at take-off were highly intercorrelated, the best model (model 3) could only account for 32.2 % of the variation in BCOMNET. Much higher coefficients of simple and multiple determination are obtained for individual subjects, when the segment lengths are constant<sup>6</sup>.

Whole-body kinematics and dynamics were good predictors, not only of TOVEL, but of VJP as well. Peak power, body weight, and amplitude of the movement were

common to almost all the best predictive models of TOVEL and VJP (models 5-7, 10-12, Table 2.6). The regression coefficients for WEIGHT and time of propulsion (TPROP) were negative, indicating an inverse relationship between these variables and the dependent variables. Surprisingly, peak negative impulse of BCOM (NEGIMMAX) was not present in the best models. NEGIMMAX has been proposed to influence VJP by allowing greater joint torques during propulsion (Cavagna 1977, Komi & Bosco 1978). In the present study, NEGIMMAX was moderately correlated with peak joint torques ( $0.35 < r < 0.70$ ), and had a significant effect on VJP ( $p = .023$ ), but its coefficient of simple determination was rather low ( $r^2 = .10$ ). With two exceptions ( $VJP = k + \text{amp} + \text{peakpwr} - \text{weight} - \text{negimmax}$ ,  $R^2 = 0.85$ ;  $VJP = k + \text{tprop} + \text{amechp} - \text{weight} - \text{negimmax}$ ,  $R^2 = 0.85$ ), negimmax was not a significant predictor of VJP when other whole-body variables were in the model. Apparently, negative phase impulse strategy is not a critical factor for vertical jump performance. It is possible that the timing of NEGIMMAX relative to the instant of lowest position of BCOM ( $t_{low}$ ) had an effect on the association between NEGIMMAX and VJP, since timing issues are important in stretch-shortening cycle movements (Cavagna 1977). This possibility warrants further study.

Peak mechanical power has been identified before as the best predictor of VJP (Dowling & Vamos 1993). In that study, PEAKPWR accounted for about 86.5% of the variation in jump height, compared with 46.4% in the present study. The difference may be explained by the fact that Dowling & Vamos normalized their power calculations by body mass. They also obtained their jump height from take-off velocity alone. A prediction model with my data including both PEAKPWR and WEIGHT accounts for 81.9% of the variation in TOVEL, which is more in agreement with Dowling & Vamos.

Although peak power is a strong predictor of VJP, it alone does not give insight into the specific aspects of performance that distinguish one jumper from another. How do good jumpers accomplish a greater power and a higher jump? Even though my models from levels three and four do not show such high coefficients of determination,

and tend to have a large number of predictors when VJP is the dependent variable, they are closer to the mechanical and physiological bases of performance (cf. Table 2.2).

Models from levels III and IV show that joint strength measures were not as important as joint torques and powers during the jump, when predicting VJP. Table 2.7 presents the best prediction models for each one of several "natural" groups of variables from levels three and four. For most of these models, high intercorrelation among predictors resulted in only one of them being in the model at a single time. Notice how predictive ability improves moving from the muscular strength measures to actual net joint torques during the jump, and then to the peak joint powers during the jumps. Bobbert & van Ingen Schenau (1990) have shown how skeletal muscle performance is very different in the ankle plantar flexors during a vertical jump, compared to performance during uniarticular actions such as those commonly used during strength testing. Skeletal muscles are expected to be able to generate greater torques during isometric than concentric actions, provided the isometric test was performed at the optimum joint angle (Lieber 1992). Furthermore, during multiarticular movements, net joint torque measures may include the action of so-called "antagonists". When that happens, the "agonist" torque is greater than the net joint torque indicates (Zajac & Gordon 1989). Finally, unilateral strength has been shown to be greater than half the bilateral strength of leg muscles (van Soest et al. 1985). All of the above should result in the peak net joint torques measured during the vertical jump being substantially lower than the strength test torques multiplied by two (cf. Tables 2.3 and 2.4).

My data show that this was not the case for hip extension (average difference was  $-25.4$  N m,  $p = .021$ ) or for ankle plantar flexion ( $-16.5$  N m,  $p = .044$ ), but it was for knee extension ( $-239.2$  N m,  $p < .001$ ). In addition, Table 2.8 shows low to moderate correlations between muscle strength and muscle performance during vertical jumping. The present data support the view that one reason why lower body strength is normally not found to be a strong predictor of VJP, may be because skeletal muscle behavior

during a vertical jump is radically different from the actions involved in isometric, isotonic and isokinetic strength tests.

**Table 2.7.** "Best" prediction models from each type of muscle-performance predictors. All of these models were significant at  $p < .0005$ .

Type of predictors	Prediction model	R <sup>2</sup>	R <sub>a</sub> <sup>2</sup>
Peak joint powers	VJP = k+hpwrmax+kpwrmax	.499	.478
	VJP = k + hpwrmax	.443	.431
Peak joint torques	VJP = k + hipmmax	.275	.260
Torques at reversals	VJP = k + hipmrev	.234	.218
Muscular strength	VJP = k + kneextis	.218	.203

**Table 2.8.** Correlations between muscle strength and muscle performance during vertical jumping.

	HIPMMAX	HIPPWRMAX	KNEMMAX	KNEPWRMAX	ANKMMAX	ANKPWRMAX
HIPEXTIS	0.421 <sup>a</sup>	0.361 <sup>a</sup>				
HIPFLXIS	0.520 <sup>a</sup>	0.376 <sup>a</sup>				
KNEEXTIS			0.332 <sup>a</sup>	0.559 <sup>a</sup>		
KNEFLXIS			0.251 <sup>b</sup>	0.547 <sup>a</sup>		
ANKPFXIS					0.152 <sup>b</sup>	0.183 <sup>b</sup>

a)  $p < 0.05$

b)  $p \geq 0.05$

Table 2.7 also shows the lower predictive ability of peak hip torque (HIPMMAX) when compared to peak hip power (HIPPWRMAX). This illustrates the importance of the muscle's ability to generate high torques at high joint angular velocities. Differences in HIPPWRMAX among subjects may be due not only to differences in muscle fiber type composition (Bosco & Komi 1979), but to differences in coordination strategies which allow the relevant muscles to act at a more advantageous range of the force/velocity curve (a lower muscle shortening velocity at the same joint angular velocity would allow the muscle to generate more force, Bobbert et al. 1986).

Among the different muscle groups, performance of the hip muscles seems to be the most closely related to VJP, as may be seen from Table 2.7. Only the knee muscle strength was a stronger predictor than its hip counterpart. This is in agreement with Pandy and Zajac (1991), who showed that gluteus maximus, together with the vastii muscles, are the major energy generators during maximum vertical jumping.

Table 2.6 shows that the sequence of joint reversals (PROTODIS, DISTOPRO, other) and the sequence of segmental peak velocity differences (PRODISTA, DISTAPRO, other) are not included in the best prediction models for VJP. Several authors have confirmed the existence of a proximal-to-distal sequence of activation of muscle groups and sequence of joint reversals during maximum VJP (Bobbert & van Ingen Schenau 1988, Hudson 1986, Pandy & Zajac 1991). Bobbert & van Ingen Schenau (1988) suggest that a close occurrence of proximal-to-distal joint reversals is desirable in order to optimize the effective energy of BCOM at take-off. This does not mean necessarily that the best jumpers use this approach and the worst do not. In the present study, neither the sequence of joint reversals ( $p = .93$ ) nor the sequence of segmental peak velocity differences ( $p = .70$ ) had a significant effect on VJP. It would be interesting to see whether VJP changes in a single subject as a result of changes in these coordination patterns.

Similarly, the time difference of joint reversals (JREVTDIF) was not an important predictor. It was neither significant as a single predictor of VJP ( $p = .48$ ), TOVEL ( $p = .48$ ), BCOMNET ( $p = .64$ ), nor when other variables were present in the models. This is in disagreement with the data from Hudson (1986), who reported a difference in sequence and timing of joint reversals ("initiation of segment extension" in her study) between the five most skilled and the five least skilled subjects. The definition of "skilled" jumpers in Hudson's study was, however, not related to vertical jump performance as defined herein, but to the ratio of counter-movement jump height to squat jump height. In addition, the present study looked at the total time difference from first

to last joint reversals, while Hudson looked at time differences between initiation of extension of adjacent segments.

This study presents several "best" models for each level of analysis, but no general, overall statistical model is reported. The theoretical model of VJP, presented in Figure 2.2, suggests that predictors from one level already include most of the information that could be provided by predictors from lower levels of analysis. This assumption was tested by building models using the best predictors from all levels of analysis. All possible subsets regression procedures were used to identify the best overall models. It was possible to find models that included variables from levels II and III in addition to TOVEL and BCOMNET (the best model from level I), but adding up to four variables at a time to  $VJP = k + tovel + bcomnet$  ( $R^2 = 0.95$ ) only improved overall  $R^2$  by 0.02. Two examples of this situation are  $VJP = k + tovel + bcomnet - ava - amp + amechp - weight$  ( $R^2 = 0.97$ ) and  $VJP = k + tovel + bcomnet -ava -hipmrev + amechp - weight$  ( $R^2 = 0.97$ ). It was not possible to add any predictors from level III to the best models from level II (i.e., none of the predictors from level III were statistically significant under those conditions). Furthermore, no combination of predictors from different levels was better than the best models from the higher level alone. Since significant models were developed even at the lowest level of analysis, it is apparent that the best models from a particular level include most of the information that could be provided by predictors from lower levels of analysis.

The horizontal take-off velocity of BCOM could have contaminated the results of this study. Subjects did not necessarily jump directly upwards, and the horizontal component of the take-off velocity may have had an effect on overall vertical jump performance. The absolute value of the horizontal velocity at take-off was relatively small, but varied considerably from subject to subject (Mean =  $0.098 \text{ m} \cdot \text{s}^{-1}$ , S.D. = 0.076). The single coefficients of correlation between horizontal take-off velocity and the dependent variables were poor (VJP,  $r = 0.23$ ; BCOMNET,  $r = 0.26$ ; TOVEL,  $r = 0.36$ ),

and only the latter was significant at  $\alpha = 0.05$ . Furthermore, horizontal velocity at take-off was not statistically significant when added to any one of the models in Table 2.6. Therefore, there is no reason to believe that horizontal take-off velocity had a significant effect in this study.

A final comment is necessary regarding the four-segment biomechanical model used. This model does not take into account the effects of using an arm swing, which is the way humans normally jump. Among other things, the arm swing allows individuals to jump about 10 cm higher (Brown et al. 1986). Part of this improvement comes from the direct contribution of the arm swing to positive vertical impulse, but part of it comes from allowing a greater force production by the lower limbs (Jensen 1989). I believe there is a trade-off between the limitations of excluding the arms, and the greater confidence in the results which comes from using a well-tested model. Although the presently identified predictor variables would probably change in magnitude when an arm swing is included in the jumping task, their relative importance for VJP would probably remain the same. Future studies can look at the predictive ability of my statistical models under that condition.

In summary, it is possible to predict the differences in VJP among a group of normal, healthy males, using different subsets of kinesiological variables as predictors. The net position of the body center of mass at take-off contributes little information to the prediction of VJP, compared to the vertical take-off velocity. Whole-body peak mechanical power is the best single predictor of VJP, but it provides little insight into the segmental actions that result in higher jumps. At a segmental level of analysis, the present data offer little support to the relevance of some coordination variables identified in previous studies, such as the sequence and timing of joint reversals. Peak joint powers and joint torques, particularly those at the hip, seem to be the main factors that distinguish good and bad jumpers. How to modify these factors by training and practice, and how

much of an effect that modification can have on VJP, are questions that warrant further study.

## Notes to Chapter II

<sup>1</sup>BIODEX Corporation: *Operations/Applications Manual for the BIODEX System*. Second Edition. P.O. Drawer S, Shirley, N.Y. 11967.

<sup>2</sup>CYBEX, A Division of Lumex, Inc.: *Isolated Joint Testing and Exercise Handbook for using CYBEX II and U.B.X.T.* 100 Spence St., Bay Shore, N.Y. 11706.

<sup>3</sup>A detailed description of these procedures may be found in Appendix A.

<sup>4</sup>Free body diagrams and a complete description of the procedures and equations used are included in Appendix B.

<sup>5</sup>For reference purposes, a correlation matrix including all dependent and predictor variables is included in Appendix H.

<sup>6</sup>Including segment lengths in the model did not help much to improve model #3. The best model obtained, including feet length in addition to HIPANGTO and ANKANGTO, was able to account for 35.0% of the variation in BCOMNET. Multiple other combinations, including all possible two-way interactions, were unable to improve this situation. However, when segment lengths were constant in the within-subjects study, the predictive ability improved to between 80 and 90% (see Chapter III, Tables 3.5 to 3.7). It is possible that the small variation in joint angles at take-off in this study restricted their predictive ability (see Table 2.4).

**CHAPTER III**  
**KINESIOLOGICAL LIMITS OF VERTICAL JUMP PERFORMANCE:**  
**DIFFERENCES WITHIN INDIVIDUALS**

**Introduction**

Differences in vertical jump performance (VJP) among individuals and changes in performance with training have been the subject of numerous studies, but little is known about VJP performance changes within single subjects from trial to trial. In addition, several variables have been proposed as potentially critical for VJP, but satisfactory conclusions on which variables are the critical factors that limit vertical jump performance have not yet been reached.

Leg strength has long been recognized as a significant predictor of VJP, but the association is only moderate ( $r \approx 0.50$ , Genuario & Dolgener 1980). Skeletal muscle behavior may be drastically different during a multiarticular movement like the vertical jump when compared to the actions normally involved in isometric, isotonic and isokinetic strength tests (Bobbert & van Ingen Schenau 1990). Therefore, other measures of skeletal muscle performance such as joint torques and powers during the actual execution of the jump should be studied as well. Indicators of utilization of the stretch-shortening cycle (Bosco et al., 1982), such as joint torques at the instant of joint reversals or maximum negative impulse of the body center of mass during counter-movement, should also be assessed. Finally, the correct pattern of coordination of segmental actions may have an effect on vertical jump performance. In a multiarticular movement like the vertical jump, angular displacements of each segment contribute to the vertical

acceleration of the body center of mass. An ideal pattern of segment actions, where proximal segments initiate their actions before the distal segments with very small delays between adjacent segments, has been observed (Bobbert & van Ingen Schenau, 1988, Hudson 1986, Pandy & Zajac, 1991). The presence of this pattern may be assessed by looking at the sequence and timing of joint reversals (Hudson 1986, Jensen & Phillips 1991), and at the segmental sequence of peak velocity differences between the proximal and distal ends of each segment (the "geometric principle", Bobbert & van Ingen Schenau 1988).

In a previous study<sup>1</sup> on 52 physically active college males, I confirmed that muscular strength of the lower limbs is relevant to VJP, but not as much as peak joint torques and peak joint powers during the execution of the jumps. In general, indicators of stretch-shortening cycle enhancement of the jump were poor predictors of VJP. Several coordination variables (sequence of joint reversals, sequence of peak velocity differences between the proximal and distal joints of each segment, and the time difference between the first and last joint reversals) were found not to be significant predictors of VJP, suggesting that differences in these coordination patterns from one subject to another have no effect on VJP.

The conclusions from my previous study are limited by their descriptive nature. Among other things, it is difficult to untangle variables that are interrelated and have an effect on VJP. Furthermore, large between-subject differences in strength or body weight or even variables that were not included in that study may obscure the relationships between other predictors and VJP. In studying the vertical jump, it is nearly impossible to experimentally manipulate some of the predictor variables independently of others, but it is possible to control the muscular strength and anthropometric characteristics of individuals by studying one subject at a time. When the physiological and anthropometric characteristics are controlled this way, any changes in VJP from trial to trial must be due to differences in motor control strategy or fatigue, allowing the

investigator to study the variation of coordination within a single individual from trial to trial, the changes in peak joint torques and powers when a particular individual performs many trials, and whether these variables show the same association with VJP as they do when different subjects are compared.

Therefore, the purpose of the present study is to look at the changes in coordination patterns, and the associated changes in kinematics and dynamics of vertical jumping, which accompany changes in VJP occurring from trial to trial in a single subject, to better understand the characteristics of maximum vertical jump performance.

## **Methods**

### **Data acquisition**

Ten normal, physically active male college students were recruited for this study. Two of them could not be analyzed due to technical problems with the ground reaction force data. All subjects performed fifty maximal vertical jumps, starting from the position of their choice, with arms akimbo. No practice trials were allowed. Subjects were asked to sit down and rest for one minute after each trial. Procedures and equipment used for data collection are detailed elsewhere<sup>2</sup>. Briefly, jumps were performed barefooted, wearing a swimsuit or pair of shorts. Reflective markers were placed on the right shoulder, hip, knee, ankle, and toe. Ground reaction forces and moments of force were collected with a Bertec force plate, sampled at 300 Hz. Video images were collected at 60 Hz to obtain the kinematic data. Kinematic data were filtered with a low-pass, fourth-order Butterworth filter with an effective cutoff frequency of 8 Hz.

Basic anthropometric data were obtained directly by measuring each subject, and used for the calculation of segmental center of mass and moment of inertia values, according to Vaughan et al. (1992).

## Data analysis

The biomechanical model used and all analytic procedures are described in detail in a previous study<sup>3</sup>. Briefly, the human body was modeled as a planar, rigid-body system comprised of four segments linked by frictionless, hinge joints. Kinematic and kinetic data were used to calculate vertical jump performance (VJP), as well as a set of potential predictor variables.

VJP was obtained directly from the body center of mass (BCOM) position data, by subtracting the vertical position of BCOM while standing from the peak vertical position of BCOM during flight:

$$VJP = z_{peak} BCOM - z_{standing} BCOM \quad (1)$$

Vertical take-off velocity (TOVEL) was obtained from

$$\dot{z}BCOM = \frac{\int_{t_0}^{t_p} F_{zp} dt}{m} \quad (2)$$

where  $F_{zp}$  is the propulsive force, obtained by subtracting body weight from the vertical ground reaction force, and  $t_0$  is the beginning of data collection.

The net vertical position of BCOM (BCOMNET) was calculated from the BCOM position data, according to

$$BCOMNET = z_{takeoff} BCOM - z_{standing} BCOM \quad (3)$$

The remaining predictor variables were calculated as described elsewhere<sup>4</sup>, and are presented in Table 3.1, organized according to the same theoretical model (see Figure 3.1). According to this model, the first level of analysis is concerned with a functional relation: the vertical position and vertical take-off velocity of the body center of mass theoretically define VJP. The second level of analysis deals with the variables that contribute more directly to the vertical position of the body center of mass at take-off and

vertical take-off velocity. These include the joint angles at take-off, and the whole-body kinematics and dynamics of the jump, respectively. The third level of analysis includes the segmental kinematics and dynamics of the jump. Note that a fourth level of analysis, concerned with the muscular strength and anthropometric characteristics of each subject, is unnecessary here since differences in performance are studied one subject at a time. On the other hand, an additional variable (trial number) must be included, to account for changes in performance that are a function of time, such as the effects of fatigue or practice.

**Table 3.1.** Potential predictor variables of vertical jump performance (*VJP*).

**TRIAL:** Sequential numbering of all trials, from beginning to end of testing, for each subject.

**LEVEL I**

**BCOMNET:** Net vertical position of the body center of mass at take-off.

**TOVEL:** Vertical take-off velocity of the body center of mass.

**LEVEL II**

**j:** Denotes a joint. *ANK* is ankles, *KNE* is knees, and *HIP* is hips.

**jANGTO:** Joint angle at take-off.

**AMECHP:** Average mechanical power of the whole body.

**AMP:** Amplitude of the movement.

**AVA:** Average vertical acceleration.

**NEGIMMAX:** Peak negative impulse of the body center of mass.

**PEAKPWR:** Peak mechanical power of the whole body.

**TPROP:** Time of propulsion.

**LEVEL III**

**DISTAPRO:** Distal-to-proximal sequence of the maximum velocity differences between proximal and distal joints for each segment.

**DISTOPRO:** Distal-to-proximal sequence of the joint reversals.

**JACCPK:** Peak positive joint acceleration during the negative phase.

**jMMAX:** Maximum net joint torque.

**jMREV:** Net joint torque at the time of joint reversal.

**jPWRMAX:** Peak joint power.

**JREVTDIF:** Time difference between first and last joint reversals.

**MMTDIFF:** Time difference between the first and last maximal joint torques.

**PRODISTA:** Proximal-to-distal sequence of the maximum velocity differences between proximal and distal joints for each segment.

**PROTODIS:** Proximal-to-distal sequence of the joint reversals.

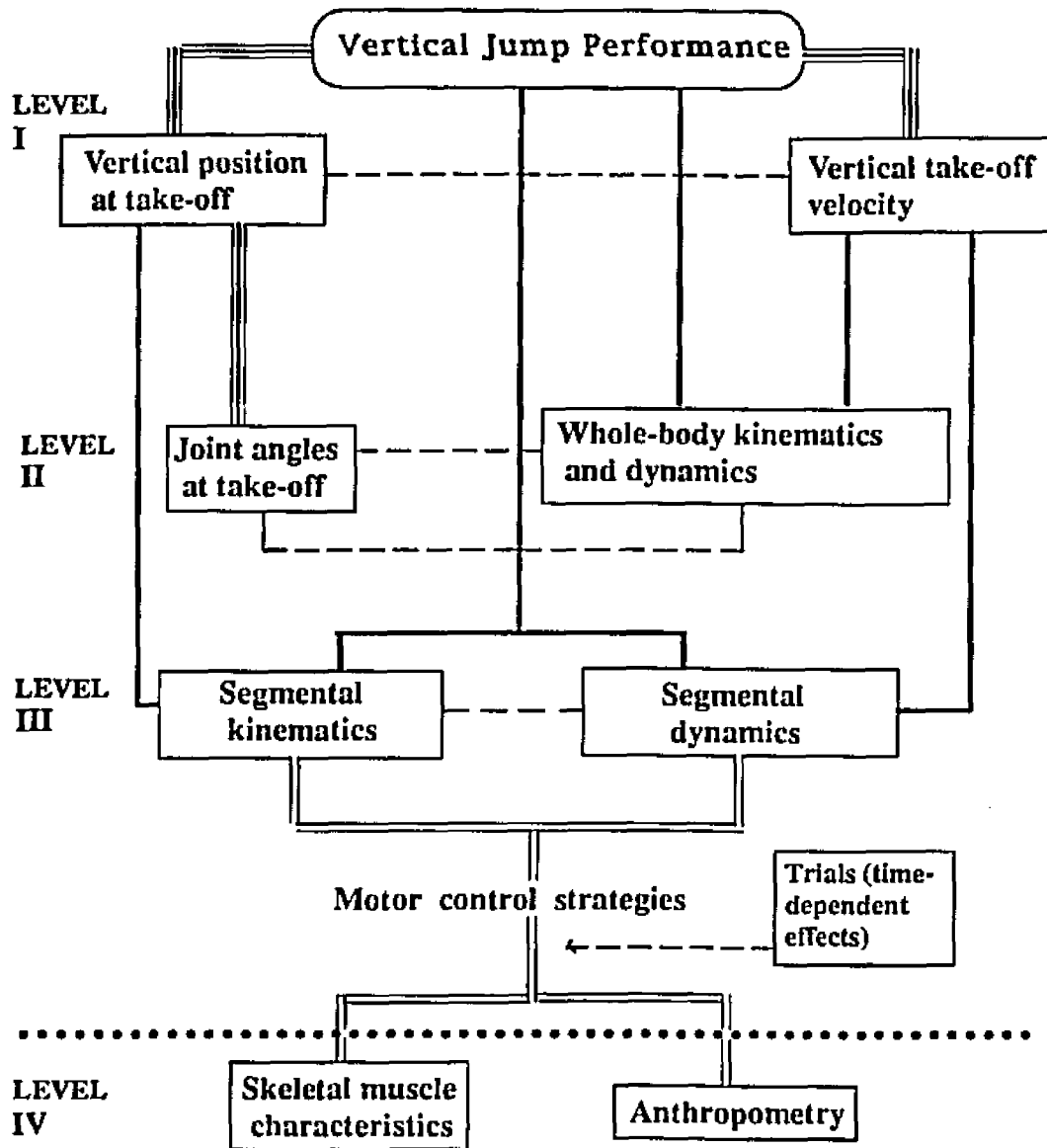


Figure 3.1. Theoretical model of vertical jump performance. Triple solid lines denote functional relations. Solid lines indicate the statistical relationships under study. Dotted lines recognize other relationships. Double lines show the basic relationships that are beyond the scope of this study.

### Statistical analysis

Multiple regression analysis techniques were applied at each level in Table 3.1 to identify the major predictor variables. The basic model used was the general linear model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_{p-1} x_{p-1} + E_j$$

where  $y$ , the dependent variable, is normally distributed;  $x_i$  is the  $i^{\text{th}}$  predictor,  $p-1$  is the number of predictors in the model,  $\beta_0$  is the intercept, and  $E_j$  are the error terms, which are independent and normally distributed. Descriptive statistics were used to verify that the basic assumption of normality of the dependent variables was met, and to investigate whether there was a reasonable variability of both dependent and predictor variables.

The assumption of uncorrelated or independent error terms was not appropriate for the within-subject design of this study. Therefore, the Durbin-Watson statistic was used to test for a significant autocorrelation of  $E_j$ . If autocorrelation exists, the tests of significance of the models and each predictor are not strictly applicable, and MSE may underestimate the variance of the error terms. Models where autocorrelation was an issue are clearly labeled. In addition, multiple regression analyses were performed one subject at a time including trial number among the predictor variables, to account for the possible effect of practice or fatigue that would result from doing 50 maximum vertical jumps.

Three of the eight subjects with complete results, an average jumper, the best jumper, and the worst jumper, were selected for the statistical model development stage. For each level of analysis, several statistical models were developed, using "all possible subsets" and "stepwise" regression techniques, and compared. Selection of several "best" models was made according to commonly used criteria: Mallows'  $C_p$  ( $C_p \cong p$ ), and  $R_u^2$  (the highest adjusted r-squared values). Interactive stepwise regression was used to verify the significance and the relative importance of each predictor in the models. These models were refined using residual analysis techniques, to check for the omission of important variables or the need for interaction terms or a curvilinear function. The

presence of outliers was determined using leverage and studentized deleted residuals; their influence was assessed using Cook's D. Finally, the aptness of each model in terms of the normality of  $E_j$  was evaluated using normal probability plots. Once the model development stage was finished, the best VJP models were tested on the remaining five subjects.

## Results

Descriptive statistics of selected variables for all eight subjects are presented in Tables 3.2 and 3.3. Overall average VJP for this study was 0.46 m. Three of these subjects were selected for the process of model development on the basis of their jump heights. Selected subjects represent average and extreme jumping performances. The average subject was selected from among other average jumpers on the basis of his large variation in VJP and good combined validity of TOVEL and BCOMNET (see Appendix C, Table C.2)<sup>5</sup>. Descriptive statistics of jump execution for the three selected subjects are presented in Tables 3.4, 3.5, and 3.6. Subject A was an average jumper (VJP = 0.439 m, C.V. = 3.8%), subject W was the worst jumper (VJP = 0.301 m, C.V. = 3.1%), and subject B was the best (VJP = .586, C.V. = 2.4%). Taking their best trials, these subjects are representative of the jumpers in my previous study: the worst jumper (0.33 m) was almost three standard deviations below the mean, the average jumper (0.47 m) was within one S.D., and the best jumper (0.61 m) was over one standard deviation above the mean. Since body mass is a relevant predictor of VJP (Table 2.6), it is important to note that these three subjects were similar in terms of body mass, weighing 70.9 kg, 71.1 kg, and 65.5 kg, respectively, compared with an average of 74.3 kg from my previous study. Standard deviations were similar, across subjects, for most variables, but subjects were clearly different in terms of take-off velocity (TOVEL), whole-body mechanics, and most segmental kinematics and dynamics. All three dependent variables: VJP, TOVEL, and

BCOMNET were normally distributed for these three subjects, as assessed from skewness and kurtosis measures.

**Table 3.2.** Descriptive statistics for all subjects (selected variables).

Subject	VJP (m)		TOVEL ( $m \cdot s^{-1}$ )		BCOMNET (m)		PEAKPWR (W)		HIPWRMAX (N m)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
DI01 (A) <sup>a</sup>	0.439	0.017	2.465	0.052	0.116	0.021	3706.0	136.1	1181.1	129.0
DI02(W) <sup>a</sup>	0.301	0.009	1.710	0.044	0.133	0.015	2079.4	56.6	653.6	67.3
DI03	0.468	0.011	2.400	0.065	0.134	0.018	2675.8	80.7	769.0	99.0
DI04	0.522	0.013	2.696	0.055	0.132	0.021	3620.1	102.1	1435.6	154.0
DI05	0.463	0.010	2.434	0.134	0.129	0.018	3783.2	243.3	1285.4	134.8
DI06	0.442	0.012	2.387	0.040	0.136	0.021	3411.8	78.0	1025.3	103.9
DI07 (B) <sup>a</sup>	0.586	0.014	2.938	0.048	0.150	0.023	4085.0	74.2	1222.4	165.7
DI08	0.453	0.013	2.418	0.040	0.146	0.018	3847.3	96.1	1351.2	112.3

a) Selected subjects for model building. A= average jumper. B= best jumper. W = worst jumper.

**Table 3.3.** Frequency table for the sequence variables (all subjects).

Subject	PROTODIS	DISTOPRO	Other sequences of joint reversals	PRODISTA	DISTAPRO	Other sequences of peak velocity diffs.
DI01 (A) <sup>a</sup>	12	0	36	48	0	0
DI02(W) <sup>a</sup>	32	0	18	50	0	0
DI03	40	0	10	48	0	2
DI04	15	0	33	48	0	0
DI05 <sup>b</sup>	0	1	48	40	0	9
DI06	34	1	14	37	0	12
DI07 (B) <sup>a</sup>	41	0	8	46	0	3
DI08	39	0	9	48	0	0

a) Selected subjects for model building. A= average jumper. B= best jumper. W = worst jumper.

b) This subject performed a "squat jump", with very small countermovement.

**Table 3.4.** Jump execution characteristics for each subject.

Variable (units)	Worst (n = 50)		Average (n = 48)		Best (n = 49)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
VJP (m)	0.301	0.009	0.439	0.017	0.586	0.014
TOVEL ( $m * s^{-1}$ )	1.710	0.044	2.465	0.052	2.938	0.048
BCOMNET (m)	0.133	0.015	0.116	0.021	0.150	0.023
HIPANGTO (rad)	3.02	0.06	2.91	0.07	3.01	0.07
KNEANGTO (rad)	3.02	0.06	3.08	0.08	3.00	0.08
ANKANGTO (rad)	2.60	0.06	2.51	0.07	2.52	0.06
TPROP (s)	0.319	0.021	0.229	0.013	0.244	0.017
AVA ( $m * s^{-2}$ )	5.40	0.44	10.78	0.66	12.08	0.77
AMP (% body height)	24.98	1.54	21.06	1.50	29.76	2.04
AMECHP (W)	1313.6	52.8	2124.1	117.2	2485.9	123.9
PEAKPWR (W)	2079.4	56.6	3706.0	136.1	4085.0	74.2
NEGIMMAX ( $kg * m * s^{-1}$ )	-64.22	8.08	-68.78	4.85	-88.53	4.35
HIPACCPK ( $rad * s^{-2}$ )	41.23	5.27	52.56	5.12	80.47	6.24
KNEACCPK ( $rad * s^{-2}$ )	27.50	4.69	23.74	9.32	40.41	7.66
ANKACCPK ( $rad * s^{-2}$ )	24.82	14.33	32.04	26.41	29.67	25.86
MMTDIFF (s)	0.099	0.042	0.111	0.027	0.109	0.033
JREVTDIF (s)	0.062	0.021	0.095	0.020	0.082	0.014
HIPMMAX (N m)	212.76	13.80	297.91	15.09	290.16	21.23
KNEMMAX (N m)	152.85	9.64	126.03	19.80	209.82	13.51
ANKMMAX (N m)	178.94	11.58	250.87	13.97	235.47	18.66
HIPMREV (N m)	209.45	15.77	283.35	20.09	287.18	22.43
KNEMREV (N m)	150.04	10.04	109.04	23.08	203.49	17.69
ANKMREV (N m)	165.51	21.54	229.66	21.19	223.38	24.53
HIPPWRMAX (W)	653.6	67.3	1181.1	129.0	1222.4	165.7
KNEPWRMAX (W)	779.1	103.9	947.7	189.0	1825.9	111.3
ANKPWRMAX (W)	966.9	133.3	1823.1	326.2	1968.9	188.3

**Table 3.5.** Coefficients of variation of dependent and predictor variables for each subject. C.V. = (S.D./mean) \* 100.

<b>Variable</b>	<b>Worst C.V. (%)</b>	<b>Average C.V. (%)</b>	<b>Best C.V. (%)</b>
VJP	3.1	3.8	2.5
TOVEL	2.6	2.1	1.6
BCOMNET	11.2	18.4	15.1
HIPANGTO	2.1	2.4	2.3
KNEANGTO	1.9	2.5	2.7
ANKANGTO	2.1	2.7	2.3
TPROP	6.7	5.6	6.8
AVA	8.2	6.1	6.4
AMP	6.1	7.1	6.9
AMECHP	4.0	5.5	5.0
PEAKPWR	2.7	3.7	1.8
NEGIMMAX	12.6	7.1	4.9
HIPACCPK	12.8	9.7	7.8
KNEACCPK	17.1	39.3	19.0
ANKACCPK	57.7	82.4	87.2
MMTDIFF	41.8	23.8	30.1
JREVTDIF	34.0	21.1	17.2
HIPMMAX	6.5	5.1	7.3
KNEMMAX	6.3	15.7	6.4
ANKMMAX	6.5	5.6	7.9
HIPMREV	7.5	7.1	7.8
KNEMREV	6.7	21.2	8.7
ANKMREV	13.0	9.2	11.0
HIPPWRMAX	10.3	10.9	13.6
KNEPWRMAX	13.3	19.9	6.1
ANKPWRMAX	13.8	17.9	9.6

**Table 3.6.** Jump execution characteristics for each subject: sequence variables.

<b>Variable (units)</b>	<b>Worst (n = 50) Frequency</b>	<b>Avrge. (n = 48) Frequency</b>	<b>Best (n = 49) Frequency</b>
PROTODIS	32	12	41
DISTOPRO	0	0	0
Other sequences of joint reversals	18	36	8
PRODISTA	50	48	46
DISTAPRO	0	0	0
Other sequences of velocity diffs.	0	0	3

Coordination variables showed similar behavior across subjects (Tables 3.4, 3.5, and 3.6). Overall, the sequence of joint reversals was proximal to distal for most trials; none of them was distal to proximal. All trials classified as "other" corresponded to a hip-ankle-knee sequence of joint reversals. Regarding sequence of peak velocity differences between proximal and distal ends for each segment, all trials from both subjects W and A were proximal to distal (PRODISTA); subject B performed three trials where the sequence was characterized as "other". Finally, average JREVTDIF and MMTDIFF were similar across subjects. However, these coordination measures were quite variable within each subject, showing coefficients of variance greater than 20% (Table 3.5).

Tables 3.7 to 3.9 show a summary of the "best" prediction models, one subject at a time<sup>6</sup>. The "best" two or three models are presented, together with the best single predictor, for each level of analysis. Trial number is always included, even for "single best predictor" models, except when not significant at  $p = .05$ , or when the single best predictor had already been included as one of the best models together with trial number. Both  $R^2$  and  $R_a^2$  values are reported, since they could point to different models as the best. When pertinent, additional information is provided for those predictors that were not included in the "best" models. Within each model, variables are presented in order of importance, according to their partial correlation coefficients.

Level one models related take-off velocity (TOVEL) and position of BCOM at take-off (BCOMNET) to VJP. At this level, TOVEL was a much stronger predictor of VJP than BCOMNET for all subjects. Partial coefficients of determination for TOVEL and BCOMNET were 0.67 vs. 0.21 for subject A; 0.54 vs. 0.04 for subject B, and 0.20 vs. 0.16 for subject W<sup>7</sup>. TOVEL and BCOMNET were poorly intercorrelated, with correlation values of -0.06, 0.06 and -0.16 for subjects A, B, and W, respectively. The worst jumper (subject W) was different from the others in two important ways: the best model could account for only 47% of the variation in VJP (compared with about 60 and

70% for the other two subjects), and there was a significant interaction between TOVEL and BCOMNET.

Level II models three and four (Tables 3.7 to 3.9) looked at relationships between VJP and whole-body kinematics and dynamics of the jump. These models show that joint angles were excellent predictors of the net position of the body center of mass at take-off. Ankle angle at take-off was the best single predictor for two of the three subjects and second best for the best subject, accounting (with the help of TRIAL) for 86, 84, and 79% of the variation in BCOMNET in subjects A, B, and W, respectively. The remaining models at this level of analysis show that it is possible to account for about 80% of the within-subject variation of TOVEL and about 68% (from 48 to 85%, depending on the subject) of VJP, using whole-body kinematics and dynamics as predictors. Peak mechanical power (PEAKPWR) was identified several times as the best single predictor of TOVEL or VJP.

Level III models included the relationship between VJP and segmental kinematics and dynamics of the jump. Tables 3.7 to 3.9 show that these models were able to account, on average, for about 40% of the variation in VJP, about 45% of the variation in TOVEL, and from 10 to 50% (depending on the subject) of the variation in BCOMNET. The most important predictors of VJP were a proximal-to-distal sequence of joint reversals (PROTODIS) and the peak hip power (HIPWRMAX), although several differences were present across subjects, such as the presence of the peak joint torques at the hip (HIPMMAX, Table 3.8, model 16), the knee (KNEMMAX, Table 3.9, model 17), and the ankle (ANKMMAX, Table 3.7, model 15). Peak ankle power (ANKPWRMAX) was also present in several of the best models. There was a tendency for those models using segmental dynamics (Table 3.7, models 21, 22, 24; Table 3.8, models 20, 22, 23; Table 3.9, models 20-22, 24) to be more powerful predictors of TOVEL and BCOMNET than those using segmental kinematics (Table 3.7, models 20, 23, 25; Table 3.8, models 21 & 24; Table 3.9, models 23 & 25).

**Table 3.7.** "Best" prediction models at each level of analysis, subject A (average jumper). Durbin-Watson test not significant ( $\alpha = .05$ ) except when noted.

Prediction model for VJP	R <sup>2</sup>	R <sub>a</sub> <sup>2</sup>	p
<b>LEVEL I</b>			
1) VJP = k + tovel + trial + bcomnet	.73	.71	<.0001
2) VJP = k + tovel + trial <sup>a</sup>	.66	.64	<.0001
<b>LEVEL II</b>			
3) BCOMNET = k + ankancto + hipangto + trial	.92	.91	<.0001
4) BCOMNET = k + ankancto + trial	.86	.86	<.0001
5) TOVEL = k + peakpwr + amechp + tprop	.79	.78	<.0001
6) TOVEL = k + amechp + tprop - trial + negimmax	.71	.68	<.0001
7) TOVEL = k + amechp + tprop - trial <sup>b</sup>	.65	.62	<.0001
8) TOVEL = k + peakpwr	.36	.35	<.0001
9) TOVEL = k + amechp - trial <sup>a</sup>	.29	.26	= .0004
10) VJP = k+tprop+amechp+peakpwr+ trial+negimmax <sup>c</sup>	.85	.83	<.0001
11) VJP = k + (tprop + amechp + peakpwr + trial <sup>a</sup> )	.83	.82	<.0001
12) VJP = k + tprop + amechp + negimmax <sup>d</sup>	.79	.77	<.0001
13) VJP = k + amp	.31	.30	= .0004
14) VJP = k + trial + peakpwr	.28	.25	= .0007
<b>LEVEL III</b>			
15) VJP = k - protodis + trial + ankmax	.52	.49	<.0001
16) VJP = k - protodis + trial + hippwrmax	.51	.48	<.0001
17) VJP = k - protodis + hippwrmax - ankpwrmax	.50	.47	<.0001
18) VJP = k + jrevtdif + trial - (trial * jrevtdif) <sup>e</sup>	.44	.41	<.0001
19) VJP = k - protodis	.42	.40	<.0001
20) TOVEL = k - protodis - trial	.31	.28	= .0002
21) TOVEL = k + ankmax + knepwrmax	.24	.21	= .002
22) TOVEL = k + ankmax	.17	.15	= .004
23) TOVEL = k - protodis	.16	.14	= .005
24) BCOMNET = k + trial + hippwrmax - hipmrev + knepwrmax	.51	.46	<.0001
25) BCOMNET = k + trial + jrevtdif <sup>a</sup>	.22	.19	= .003
26) BCOMNET = k + trial + hipmrev <sup>f</sup>	.27	.24	= .0008
27) BCOMNET = k + trial + protodis <sup>a g</sup>	.19	.16	= .008

a) Durbin-Watson test for autocorrelation was inconclusive.

b) Other models not included ( $n < 5$ ) were statistically significant, with  $R^2 = 0.64$  and lower.

c) Negimmax is strictly not a significant predictor in this model ( $p = .051$ ).

d) Other models not included ( $n > 10$ ) were statistically significant, with  $R^2 = 0.77$  and lower.

e) Other models not included ( $n < 5$ ) were statistically significant, with  $R^2 = 0.15$  and lower.

f) Hipmrev is not a significant predictor ( $p = .091$ ).

g) Protodis is not a significant predictor ( $p = .089$ ).

**Table 3.8.** "Best" prediction models at each level of analysis, subject B (best jumper).  
Durbin-Watson test not significant ( $\alpha = .05$ ) except when noted.

Prediction model for VJP	R <sup>2</sup>	R <sub>a</sub> <sup>2</sup>	p
<b>LEVEL I</b>			
1) VJP = k + tovel	.61	.60	< .0001
<b>LEVEL II</b>			
2) BCOMNET = k+hipangto+kneangto+trial+ankangto <sup>b</sup>	.94	.93	< .0001
3) BCOMNET = k + kneangto + trial	.88	.87	< .0001
4) BCOMNET = k + ankangto	.84	.84	< .0001
5) TOVEL = k + tprop + amechp + peakpwr <sup>b</sup>	.87	.87	< .0001
6) TOVEL = k + tprop + amechp - negimmax - trial	.76	.74	< .0001
7) TOVEL = k + tprop + amechp - negimmax <sup>c</sup>	.74	.72	< .0001
8) TOVEL = k - negimmax - trial <sup>a</sup>	.54	.52	< .0001
9) TOVEL = k - trial + peakpwr <sup>a</sup>	.45	.43	< .0001
10) VJP = k + tprop + amechp + peakpwr	.71	.70	< .0001
11) VJP = k - ava + amechp + peakpwr	.71	.70	< .0001
12) VJP = k + tprop + amechp <sup>d</sup>	.63	.61	< .0001
13) VJP = k - negimmax - trial	.38	.35	< .0001
14) VJP = k + peakpwr - trial	.29	.26	= .0003
<b>LEVEL III</b>			
15) VJP = k + ankaccpk + hippwrmax	.44	.41	< .0001
16) VJP = k + hipmmax - trial + ankpwrmax	.44	.40	< .0001
17) VJP = k + hipmrev - trial + ankpwrmax <sup>e</sup>	.41	.37	< .0001
18) VJP = k + hipmmax - trial	.38	.36	< .0001
19) VJP = k + hippwrmax	.36	.34	< .0001
20) TOVEL = k + hippwrmax - trial	.59	.57	< .0001
21) TOVEL = k - kneaccpk <sup>a</sup>	.18	.16	= .002
22) TOVEL = k + hippwrmax	.54	.54	< .0001
23) BCOMNET = k + ankpwrmax	.28	.26	= .0001
24) BCOMNET = k - prodista <sup>a</sup>	.01	.00	= .414

a) Durbin-Watson test for autocorrelation was significant.

b) Durbin-Watson test for autocorrelation was inconclusive.

c) Other models not included ( $n > 10$ ) were statistically significant, with  $R^2 = 0.55$  and lower.

d) Other models not included ( $n > 10$ ) were statistically significant, with  $R^2 = 0.54$  and lower.

e) Other models not included ( $n < 5$ ) were statistically significant, with  $R^2 = 0.23$  and lower.

**Table 3.9.** "Best" prediction models at each level of analysis, subject W (worst jumper).  
Durbin-Watson test not significant ( $\alpha = .05$ ) except when noted.

Prediction model for VJP	R <sup>2</sup>	R <sub>a</sub> <sup>2</sup>	p
<b>LEVEL I</b>			
1) VJP = k + tovel + bcomnet - (tovel * bcomnet) <sup>b</sup>	.47	.44	< .0001
2) VJP = k + tovel <sup>a</sup>	.20	.18	= .001
<b>LEVEL II</b>			
3) BCOMNET = k + ankangto + hipangto <sup>b</sup>	.80	.79	< .0001
4) BCOMNET = k + ankangto - trial <sup>b</sup>	.79	.78	< .0001
5) TOVEL = k + peakpwr + amechp + tprop - amp	.70	.67	< .0001
6) TOVEL = k + peakpwr + tprop + amechp <sup>b</sup>	.67	.65	< .0001
7) TOVEL = k + peakpwr - negimmax <sup>c</sup>	.59	.57	< .0001
8) TOVEL = k + peakpwr	.53	.52	< .0001
9) VJP = k + amechp + tprop + negimmax <sup>b</sup>	.48	.45	< .0001
10) VJP = k + amechp + tprop <sup>b</sup>	.43	.40	< .0001
11) VJP = k + amechp + amp <sup>a</sup>	.39	.36	< .0001
12) VJP = k + amechp - ava <sup>b d</sup>	.33	.30	< .0001
13) VJP = k + amechp <sup>b</sup>	.21	.19	< .0001
14) VJP = k + peakpwr <sup>a</sup>	.10	.08	= .026
<b>LEVEL III</b>			
15) VJP = k + hippwrmax - protodis - trial <sup>b</sup>	.34	.30	= .0002
16) VJP = k + hippwrmax - protodis	.28	.25	= .0004
17) VJP = k - knemmax - protodis <sup>b e</sup>	.23	.19	= .002
18) VJP = k + hippwrmax	.19	.17	= .002
19) VJP = k - knemmax <sup>a</sup>	.12	.10	= .015
20) TOVEL = k + ankpwrmax + ankmmmax + hipmrev	.51	.48	< .0001
21) TOVEL = k + ankpwrmax + ankmmmax + hipmmax	.50	.46	< .0001
22) TOVEL = k + ankpwrmax	.30	.28	< .0001
23) TOVEL = k - trial + hipaccpk	.16	.12	= .017
24) BCOMNET = k + knepwrmax	.08	.06	= .048
25) BCOMNET = k - kneaccpk	.10	.09	= .022

a) Durbin-Watson test for autocorrelation was significant.

b) Durbin-Watson test for autocorrelation was inconclusive.

c) Other models not included (n = 6) were statistically significant, with R<sup>2</sup> = 0.57 and lower.

d) Other models not included (n < 5) were statistically significant, with R<sup>2</sup> = 0.25 and lower.

e) Other models not included (n < 5) were statistically significant, with R<sup>2</sup> = 0.10 and lower.

One "summary" model was created for each level, using the information from Tables 3.7 to 3.9, to be tested on the rest of the subjects. Level I included TRIAL, TOVEL, and BCOMNET, regardless of the findings on Tables 3.7 to 3.9. Summary models for the other two levels were created by including all predictors that were relevant for at least two of the three subjects. Table 3.10 shows the resulting coefficients of multiple determination ( $R^2$ ), the overall significance of the model for each subject, and whether each predictor was significant or not given the other predictors in the model.

**Table 3.10.** Summary model tests on five subjects. "Yes" and "No" refer to whether the particular predictor was significant for that particular subject.

	DI03	DI04	DI05	DI06	DI08
<b>Level I</b>					
<b>R<sup>2</sup></b>	0.50	0.37	0.27	0.55	0.56
<b>p</b>	< 0.0005	< 0.0005	= 0.003	< 0.0005	< 0.0005
Trial	Yes	No	No	No	Yes
Tovel	Yes	Yes	Yes	Yes	Yes
Bcomnet	No	No	No	Yes	No
<b>Level II</b>					
<b>R<sup>2</sup></b>	0.79	0.72	0.75	0.66	0.79
<b>p</b>	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.0005
Trial	Yes	No	Yes	Yes	No
Peakpwr	Yes	Yes	Yes	Yes	Yes
Amechp	Yes	Yes	Yes	Yes	Yes
Tprop	Yes	Yes	Yes	Yes	Yes
Amp	No	No	No	No	No
Negimmax	No	No	Yes	Yes	No
<b>Level III</b>					
<b>R<sup>2</sup></b>	0.29	0.15	0.16	0.11	0.56
<b>p</b>	= 0.003	= 0.152	= 0.044	= 0.276	< 0.0005
Trial	No	No	Yes	No	Yes
Protodis	Yes	No	No	No	No
Hippwrmax	Yes	Yes	No	No	Yes
Ankpwmax	No	No	No	No	Yes

**Trial number.**

Trial number (TRIAL) was included as a potential predictor during model development to account for the possibility of practice or fatigue effects on the dependent variables. These effects were most apparent in subjects B and A, but not in any consistent pattern: the coefficient for TRIAL was sometimes positive and sometimes negative (see Tables 3.7, 3.8, and 3.11). Plots of VJP vs. TRIAL in Figure 3.2 show that there were fatigue and practice effects depending on the subject, but only the best jumper's correlation coefficient was statistically significant. TRIAL was significantly correlated with other predictors, suggesting that several aspects of jump execution, as well as actual jump performance, changed over time (Table 3.11).

**Table 3.11.** Correlations of TRIAL with selected variables for each subject.

Variable	TRIAL (Worst)	TRIAL (Average)	TRIAL (Best)
VJP	-0.16 <sup>b</sup>	0.27 <sup>b</sup>	-0.39 <sup>a</sup>
TOVEL	-0.28 <sup>b</sup>	-0.36 <sup>a</sup>	-0.52 <sup>a</sup>
BCOMNET	-0.11 <sup>b</sup>	0.37 <sup>a</sup>	0.06 <sup>b</sup>
TPROP	0.47 <sup>a</sup>	0.12 <sup>b</sup>	-0.52 <sup>a</sup>
AVA	-0.51 <sup>a</sup>	-0.24 <sup>b</sup>	0.43 <sup>a</sup>
AMP	0.35 <sup>a</sup>	0.43 <sup>a</sup>	-0.36 <sup>a</sup>
AMECHP	-0.42 <sup>a</sup>	0.07 <sup>b</sup>	0.30 <sup>a</sup>
PEAKPWR	-0.43 <sup>a</sup>	-0.72 <sup>a</sup>	-0.06 <sup>b</sup>
NEGIMMAX	-0.28 <sup>a</sup>	-0.17 <sup>b</sup>	0.01 <sup>b</sup>
KNEACCPK	0.05 <sup>b</sup>	0.51 <sup>a</sup>	0.61 <sup>a</sup>
MMTDIFF	0.37 <sup>a</sup>	-0.05 <sup>b</sup>	-0.38 <sup>a</sup>
JREVTDIF	-0.39 <sup>a</sup>	-0.56 <sup>a</sup>	-0.17 <sup>b</sup>
KNEMMAX	-0.04 <sup>b</sup>	-0.19 <sup>b</sup>	0.41 <sup>a</sup>
ANKMMAX	-0.54 <sup>a</sup>	-0.47 <sup>a</sup>	0.42 <sup>a</sup>
KNEMREV	-0.10 <sup>b</sup>	-0.08 <sup>b</sup>	0.41 <sup>a</sup>
ANKMREV	-0.55 <sup>a</sup>	-0.37 <sup>a</sup>	0.36 <sup>a</sup>
HIPPWRMAX	0.17 <sup>b</sup>	-0.25 <sup>b</sup>	-0.45 <sup>a</sup>
KNEPWRMAX	-0.33 <sup>a</sup>	-0.30 <sup>a</sup>	0.26 <sup>b</sup>
ANKPWRMAX	-0.27 <sup>b</sup>	-0.57 <sup>a</sup>	-0.02 <sup>b</sup>

a) Correlation is significant ( $p < 0.05$ ).

b) Correlation is not significant ( $p > 0.05$ ).

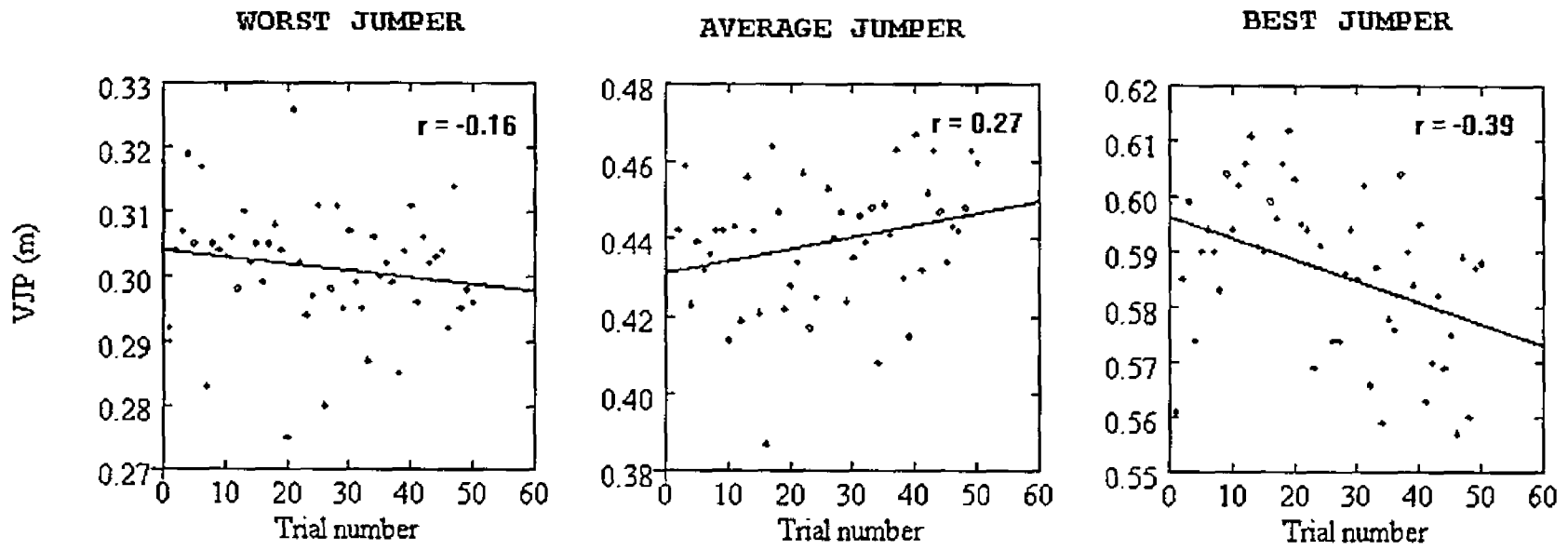


Figure 3.2. Vertical jump performance (VJP) vs. trial number. Subjects were required to sit down for one minute after each trial.

## Discussion

The purpose of this paper was to study the differences in jump execution variables that accompany differences in vertical jump performance within single subjects. A major concern with a descriptive study of this type is whether the amount of variation in the predictor and dependent variables is enough to allow for multiple regression analysis. Several authors have reported that the vertical jump, especially the propulsive phase, is performed repeatedly in the same way by the same subject (Bobbert et al. 1987a, Dyhre-Poulsen et al. 1991, Hudson 1986, Jensen & Phillips 1991). Zajac et al. (1981) reported the same type of behavior during the propulsive phase in cats. Dyhre-Poulsen et al. (1991) mentioned that unskilled subjects were more variable than skilled ones, but neither the latter nor the other authors reported quantitative data to allow for evaluation of the within-subject variability. The coefficients of variation from Table 3.5 allow for comparison of the standard deviations of variables measured in different units (Table 3.4), making this type of evaluation possible.

Most of these coefficients of variation are small, i.e., less than 10%. On the other hand, a few variables show higher coefficients of variation. The high coefficients obtained for peak acceleration of the ankle during the negative phase (ANKACCPK) suggest that the filtering process did not eliminate all the noise at this joint, where the adjoining segments are short and small displacements in their distal ends result in large changes in joint angle. Since this problem was even present when the subject was standing still, ANKACCPK was not included in the analysis. Two other variables show high coefficients of variation: MMTDIF and JREVTDIF. These are time differences between the occurrence of clearly defined events, and because I have no reason to believe that there is considerable error in the detection of those events, I conclude that the coefficients represent large physiological variability.

Variability of the sequence variables has been summarized in Table 3.6. The sequence of maximum velocity differences between proximal and distal joints at each segment was almost always PRODISTA. The sequence of joint reversals was either PROTODIS or OTHER. Therefore, the results of this study are limited to those coordination patterns.

Theoretically, TOVEL and BCOMNET should account for all of the variation in VJP. However, prediction of VJP using those two variables was not as good in this study (cf. models at level I in Tables 3.7, 3.8, and 3.9) as has been reported previously for between-subject differences<sup>8</sup>. The small jump-to-jump variability in VJP and TOVEL has some effect on this: a smaller variation in the dependent variables causes the multiple coefficients of determination to be smaller, even if everything else remained the same. This is because measurement error becomes relatively more important. The measurement error of TOVEL and BCOMNET combined, obtained by calculating the square root of the Mean Square for Error from each model, was estimated to be about 17 mm for the between-subjects study, and about 8 mm for the present study<sup>9</sup>. Furthermore, BCOMNET had a small effect by itself, accounting for about 17% of the variation in VJP for subject A ( $p = .004$ ), and for about 12% of the variation in VJP for subject W ( $p = .014$ ). For subject B, it did not achieve significance ( $p = .234$ ). The restricted predictive ability of BCOMNET was not due to a small variability of this parameter, as may be seen from the data on Table 3.9. It is possible that BCOMNET is only a marginally relevant predictor of VJP, but in that case TOVEL should be a much stronger predictor than it actually was. Another possibility is that there was considerable error involved in the calculation of BCOMNET. This error would probably be related to an inaccurate determination of the instant of take-off on the video data relative to the ground reaction force data, and not to inaccurate measurements of the position of BCOM; the joint angles at take-off were excellent predictors of BCOMNET, as would be expected<sup>10</sup>. I think that the small variability of VJP relative to the size of the error term limited the predictive

ability of BCOMNET and TOVEL. Any conclusions involving these two variables must be taken cautiously in light of this problem, especially regarding subject W.

Keeping in mind this limitation, it should be pointed out that the small, statistically non-significant correlations between TOVEL and BCOMNET suggest that the maximization of one variable was not achieved at the expense of the other. This would not agree with the proposed "compromise" between BCOMNET and TOVEL of Bobbert & van Ingen Schenau (1988).

Due to the within-subject design of this study, there is a concern about the assumption of independence of the error terms. This assumption was tested using the Durbin-Watson D-statistic. Tables 3.7 to 3.9 show that for most of the models the assumption was correct, since the autocorrelations were not significant. For several models, however, the autocorrelations were either significant or "inconclusive". For those cases, the error terms are likely non-independent, and no statistical inferences should be made about them. Since the purpose of this study is mainly descriptive, their p-values may be used as mere guidelines.

The theoretical model in Figure 3.1 does not include horizontal take-off velocity as a potential predictor of VJP. While it is true that the horizontal motion is deliberately excluded from the definition of VJP (equation 1), it is also true that the predictive power of some variables could be disguised by "wasted effort" that results in horizontal displacement of BCOM. Horizontal take-off velocity of BCOM was calculated from the BCOM positions at take-off and at the peak, and the results analyzed. The absolute value of horizontal take-off velocity was small, but quite variable from trial to trial (Mean  $\cong$   $0.055 \text{ m} \cdot \text{s}^{-1}$ , S.D. = 0.041). Nevertheless, the correlations between this variable and VJP were smaller than 0.25, and non-significant. Horizontal take-off velocity was not a relevant additional predictor to any of the models in Tables 3.7 to 3.9, except for two cases from Table 3.7 where TOVEL was the dependent variable. Model #6 was improved from  $R^2 = 0.71$  to 0.74 ( $\text{TOVEL} = k + \text{amechp} + \text{tprop} - \text{trial} + \text{negimax} -$

horvelab), and model #20 was improved from  $R^2 = 0.31$  to 0.42 (TOVEL = k - protodis + horvelab - trial). Overall, horizontal take-off velocity was not a significant predictor of VJP.

### **Predictors of vertical jump performance.**

At level II of analysis, results for the average jumper show that models #10, #11 and #12 (Table 3.7) account for about 79 to 85% of the variation in VJP. Time of propulsion (TPROP) and average mechanical power (AMECHP) were common to all of these models. Peak negative impulse (NEGIMMAX) was a relevant predictor, but it failed to achieve significance in model 10 ( $p = .051$ ). PEAKPWR was a significant predictor, but it clearly was not as relevant as has been reported for between-subject studies. Dowling & Vamos (1993) reported a coefficient of determination of 0.86 for peak mechanical power, adjusted for body weight. In a previous study<sup>11</sup>, I had found that PEAKPWR alone could account for about 46% of the variation in VJP between subjects. Model 14 in Table 3.7 shows that even with the help of TRIAL, peak mechanical power could only account for about 28% of the variation in VJP. Furthermore, model 12 shows that VJP could be adequately predicted without PEAKPWR. The best single predictor of VJP was amplitude of the movement (AMP, 31%, model 13).

Results from the best jumper are similar to those above (see Table 3.8, models 10-14). PEAKPWR and AMECHP were the most commonly found predictors, followed by TPROP. NEGIMMAX and PEAKPWR were the best single predictors. The best models could account for about 71% of the variation in VJP. Peak mechanical power by itself was able to account for 29%. Subject W (worst jumper) was somewhat different (Table 3.9, models 9-14): PEAKPWR was only a marginally significant predictor of VJP (Table 3.9, model 14), while average mechanical power (AMECHP) was present in all of the "best" models, and TPROP was present in two.

The prediction of VJP for the average jumper using segmental kinematics and dynamics of the jump shows a surprising result (Table 3.7, models 15-19): the sequence

of joint reversals (PROTODIS) was the best single predictor, accounting for about 42% of the variation in VJP, and PROTODIS was a significant predictor in all three "best" models. However, the negative coefficient for PROTODIS indicates a tendency for trials where the sequence was proximal-to-distal to result in lower jumps than when it was otherwise. The same thing occurred with subject W, while PROTODIS was non-significant for subject B. Evidence has been provided showing that a proximal-to-distal sequencing of joint reversals should be the ideal pattern for maximum VJP (Bobbert & van Ingen Schenau 1988, Hudson 1986, Pandy & Zajac 1991, van Ingen Schenau 1989a & 1989b). It is possible that a pattern of coordination where the hip joint reversal happens before the others (the pattern found in all trials in this study) is important for reasons other than those suggested by the authors above. Whatever the case, it is clear that in two out of three subjects, a HIP-ANKLE-KNEE pattern of coordination resulted in better jumps than a HIP-KNEE-ANKLE pattern.

Other coordination-related variables showed a weak association with VJP. Table 3.12 shows the correlation coefficients between VJP and two coordination variables, MMTDIF and JREVTDIF, for each subject. Only one of the correlations was significant. This particular case is described in detail in Table 3.7, model 18; the coefficient for JREVTDIF was positive, which would suggest that trials where the joint reversals were more tightly coupled tended to result in lower jumps. However, the significant interaction between JREVTDIF and TRIAL makes the interpretation of the main effects very difficult.

**Table 3.12.** Correlations between VJP and two coordination variables for each subject.

Variable	VJP (Worst)	VJP (Average)	VJP (Best)
JREVTDIF	0.10	0.54 <sup>a</sup>	0.05
MMTDIFF	0.05	0.02	0.08

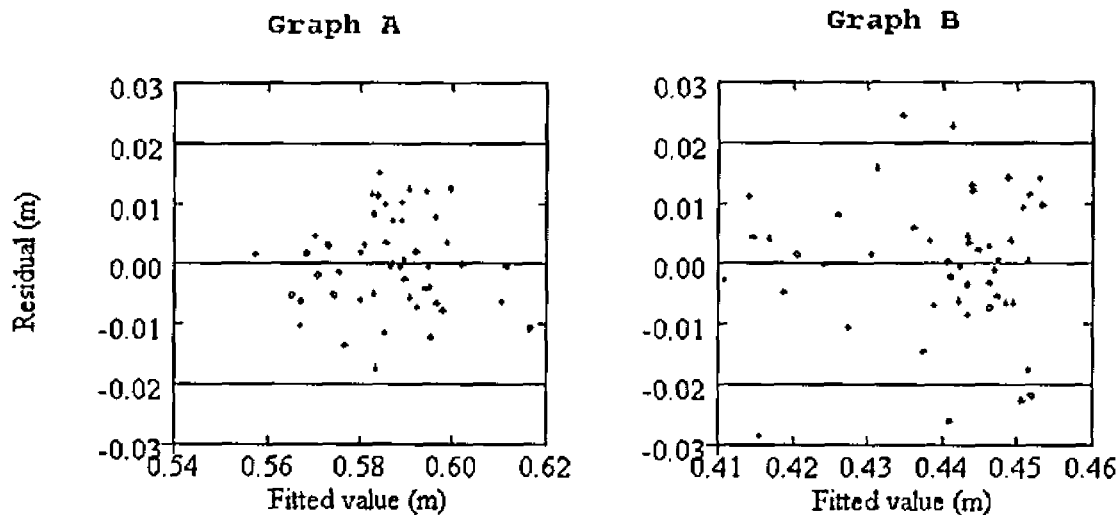
a) Correlation is significant ( $p < .0005$ ).

The other relevant predictors of VJP at the segmental level of analysis were HIPPWRMAX and ANKPWRMAX. Peak hip power was the single best predictor for subjects B (Table 3.8, model 19) and W (Table 3.9, model 18). It was also present in several "best" models of subjects A (Table 3.7, models 16 & 17) and W (Table 3.9, models 15 & 16). This is in agreement with between-subject results reported previously<sup>12</sup>. Peak ankle power was relevant in models for subject A (Table 3.7, model 17) and for subject B (Table 3.8, models 16 & 17). These two peak joint powers were very weakly associated with PROTODIS, but were significant predictors of VJP even in models that included PROTODIS and TRIAL (Table 3.7, models 16 & 17; Table 3.8, models 16 & 17; Table 3.9, model 15 & 16). Assuming that skeletal muscle characteristics are accounted for by the study design, and that muscle activation is always maximum during maximum vertical jumping (Pandy et al. 1990), something else in the coordination besides the sequence of joint reversals and the effects of fatigue or practice affected these peak joint powers which, in turn, had a significant effect on VJP.

There were some differences in the models obtained from an average, a poor, and a good jumper, but the differences were not systematic (cf. Tables 3.7, 3.8, and 3.9). This is preliminary evidence that "good" and "bad" jumpers, at this level of performance, may not differ in the way that VJP is affected by changes in coordination or other predictor variables. When the "summary" models, created from predictors that were common to two or all of the three subjects, were tested on other subjects, acceptable results were obtained (cf. Table 3.10), supporting the assumption that the performance of these three subjects was representative of the performance of the group. Several variables behaved rather consistently, from subject to subject, as predictors of VJP. Take-off position of the body center of mass was seldom significant, while take-off velocity was significant always. At level II, peak and average mechanical power, together with time of propulsion, were always significant, and the model  $R^2$  values were very similar among

subjects. Level III showed more variation in the significance of the predictors from one subject to another, but peak hip power was a relevant predictor for most subjects.

It is important to point out that the models discussed are reasonable prediction models, but in most cases were not able to account for all trials appropriately. Figure 3.3 shows plots of the residuals vs. the fitted values for two of the models used to predict VJP. Graph (A) shows the ideal situation: the residuals are distributed randomly and are close to zero, as happened with that particular model which produced no outliers or cases with large leverage. Graph (B) shows a more common situation: the model could not account for all the trials, resulting in scattered residuals (note that several points lie beyond the reference lines placed at 2 cm). Outlying trials for each subject were not always the same, but rather changed from model to model, suggesting that they simply reflected the limitations of the different models.



**Figure 3.3.** Residuals vs fitted values. Graph (A) shows the plot for model 10, Table 3.8. Graph (B) shows the plot for model 15, Table 3.7. Reference lines were placed two centimeters above and below zero.

**Summary.**

This study has described the changes that occur in some jump execution parameters which accompany changes in vertical jump performance within single individuals. The changes in VJP and TOVEL from trial to trial were rather small, making the analysis more difficult to interpret. It was possible, nevertheless, to predict VJP from whole-body or segmental kinematics and dynamics. Vertical take-off velocity (TOVEL) was a strong predictor of VJP differences within subjects, but could not account for more than 66% of the variation. Although this points to take-off position (BCOMNET) of the body center of mass as a potentially very relevant predictor, the association between BCOMNET and VJP was rather poor, probably due to error in its measurement.

Whole-body peak (PEAKPWR) and average (AMECHP) mechanical powers, as well as the time of propulsion (TPROP), were strong predictors of VJP, although PEAKPWR was not as strong a predictor as it was in the between-subjects study. Finally, peak negative impulse of BCOM (NEGIMMAX) was also a relevant factor, although not as strong as the other three. Considering the small variation in VJP and TOVEL, and the absence of body weight as a predictor due to study design, the strength of the models obtained in this part of the study was remarkably large, compared with those obtained from the between-subject differences.

At the segmental level of analysis, PROTODIS was among the stronger predictors, but the present data do not support the view that a proximal-to-distal sequence of joint reversals is the ideal for maximum vertical jump performance. PROTODIS had been shown to have no significant effect on VJP in the between-subject study, probably because large between-subject differences in other variables neutralized any effects of the sequence of joint reversals. The effect of the sequence of peak velocity differences between proximal and distal ends for each segment on VJP could not be assessed, due to the lack of variation in this coordination variable; the consistent use of PRODISTA by most of the subjects was, however, remarkable. Other indicators of coordination (timing

of joint reversals and timing of peak joint torques) were mostly irrelevant. Finally, a few joint powers and torques (particularly HIPPWRMAX) were found to be important predictors of VJP. HIPPWRMAX had also been the single best predictor of VJP for the between-subjects study. Overall, these models were not as strong as those obtained in my previous study of between-subject differences, but given the small variation of VJP in each of these subjects, the strength of the relationships is noteworthy.

Single individuals showed some variability in VJP over many trials, even when attempting to achieve maximum height on every trial. Since skeletal muscle characteristics and anthropometric characteristics were constant, this variability must be due to variations in motor control strategy or fatigue. Fatigue was only apparent in the best jumper, but even after statistically controlling for fatigue or practice effects, there was considerable variation in VJP. Although a certain level of random variation in motor control may have been present, variations apparently attempted to maximize the joint powers and torques, as well as most of the whole-body kinematics and dynamics, in order to maximize VJP. Several previously proposed indicators of coordination were tested in an attempt to identify the motor control strategy responsible for optimum VJP, without success. This issue undoubtedly warrants further study.

### Notes to Chapter III

<sup>1</sup>Reported in this dissertation as Chapter II.

<sup>2</sup>See Chapter II.

<sup>3</sup>Ibid, pp. 10-17.

<sup>4</sup>Ibid, pp. 13-17.

<sup>5</sup>Table C.2 shows the combined validity of TOVEL and BCOMNET for all eight subjects, as well as a comparison of the discrepancy between measured and calculated jump height and the range of VJP for each subject. Subject #7 shows the best characteristics among the "average jumpers".

<sup>6</sup>Similar tables with the "best" prediction models for subjects 3, 4, 5, 6, and 8 are included in appendix G.

<sup>7</sup>The coefficients presented for each subject correspond to the partial coefficient obtained when all other variables in model #1 for that particular subject were already in the model.

<sup>8</sup>Chapter II, table 2.6.

<sup>9</sup>The analysis of some possible sources of error, and precision in the measurement of VJP, TOVEL and BCOMNET is presented in Appendix C of the dissertation.

<sup>10</sup>Ibid.

<sup>11</sup>Table 2.6, model 13.

<sup>12</sup>Ibid, model 18.

## CHAPTER IV

### SUMMARY AND CONCLUSIONS

This study has identified factors that may be critical for vertical jump performance (VJP). Chapter II examined the kinesiological factors associated with differences in VJP among subjects; Chapter III examined the kinesiological variables that accompany changes in VJP from trial to trial within a single individual. The within-subject study controlled for strength and other individual characteristics which might have played an important role in the between-subjects study. The present chapter presents a final discussion of the major findings, after summarizing and comparing the results. Both the results and the discussion are ordered according to the hypotheses from Chapter I.

#### **Hypothesis 1.**

*The vertical take-off velocity of the body center of mass is able to explain more of the variation in vertical jump performance than the vertical position of the body center of mass at take-off.*

Vertical take-off velocity dominated VJP for the between-subject differences: the partial coefficients of determination for TOVEL and BCOMNET were 0.94 and 0.26, respectively. When both variables were present in the model, the multiple coefficient of determination was 0.95. Although coefficients of determination for the within-subject differences were much smaller, TOVEL was a stronger predictor of VJP than BCOMNET: partial coefficients of determination were, respectively, 0.67 vs. 0.21 for the average jumper; 0.54 vs. 0.04 for the best jumper; and 0.20 vs. 0.16 for the worst jumper. Hypothesis #1 is accepted for both parts of the study.

Lower multiple coefficients of determination (between 0.47 and 0.73), obtained for the within-subject differences, suggest that the errors involved in the calculation of TOVEL and BCOMNET was relatively large, compared with the small variation in VJP from trial to trial. Although I found both variables to be significantly associated with VJP, the potential for error in measuring BCOMNET could easily exceed the amount of information that this variable is contributing to VJP. Future studies dealing with this particular variable must verify that BCOMNET can be measured with greater accuracy. Based on the present observations, it would be necessary to identify the instant of take-off with an error smaller than 3.0 ms, equivalent to an error in BCOMNET of 8 mm<sup>1</sup>.

Bobbert & van Ingen Schenau (1988) have proposed that optimum coordination in vertical jumping seeks a compromise between maximum take-off velocity of BCOM and maximum position of BCOM at take-off. According to the present data, there did not seem to be a compromise between TOVEL and BCOMNET. The low and statistically non-significant correlations found in both the between-subjects and within-subjects studies between these two variables suggest that one is not improved at the expense of the other. It is possible that the motor control of human vertical jumping actually attempts to maximize take-off velocity alone.

### **Hypothesis 2.**

*The ankle joint angle at take-off is able to account for more of the variation in take-off net vertical position of BCOM than either the knee or the hip joint angles at take-off.*

No support for this hypothesis was found in the between-subjects study, where ANKANGTO was a significant predictor of BCOMNET ( $r^2 = 0.21$ ), but KNEANGTO was slightly more powerful ( $r^2 = 0.24$ ); the best model could only account for 32% of VJP variation. Large between-subject differences in segment lengths had an effect on the prediction of between-subject differences in BCOMNET which could not be elucidated. On the contrary, within-subject differences showed that ANKANGTO was the single best

predictor of BCOMNET for two of the three subjects and second best for the third subject, accounting (with the help of TRIAL) for between 79 and 86% of the variation in BCOMNET. Hypothesis #2 is accepted for the within-subject study, but rejected for the between-subject study.

Bobbert et al. (1986) proposed that the ankle angle should be as high as possible at take-off, and suggested that the plantar flexion which occurs at the end of propulsion adds about 10 cm. to jump height. From my within-subject study, I conclude that maximizing BCOMNET is strongly associated with maximizing ANKANGTO (differences in BCOMNET among subjects were only moderately correlated to ankle angle at take-off). It is not possible to determine from my data whether a third characteristic (i.e., differences in peak ankle power output) was responsible for this relationship.

### **Hypothesis 3.**

*At least 80% of the between-subjects variation (50% of the within-subjects variation) in vertical take-off velocity of BCOM can be accounted for by a statistical model which includes, as predictors, body mass, body height, and whole-body kinematics and dynamics.*

Data from both Chapters II and III strongly support this hypothesis. The best models were able to account for about 90% of the between-subjects variation in TOVEL, and about 70 to 87% of the within-subjects TOVEL variation. The hypothesis is accepted.

### **Hypothesis 4.**

*At least 64% of the between-subjects variation (40% of the within-subjects variation) in VJP can be accounted for by a statistical model that includes, as predictors, body mass, body height, and whole-body kinematics and dynamics.*

This hypothesis was also fully confirmed by the data from both studies. The best models accounted for about 88% of the between-subjects variation in VJP, and about 48

to 83% (depending on the subject) of the within-subjects VJP variation. Hypothesis #4 is accepted.

The strongest predictor at the whole-body level was, overall, peak mechanical power (PEAKPWR,  $r = 0.68$  for between-subjects and  $r \approx 0.53$  for within-subject differences), followed by average mechanical power (AMECHP,  $r = 0.66$  for between-subjects and  $r \approx 0.46$  for within-subject differences). These results are consistent with the wide use of vertical jumping as a test of power. A recent study by Dowling and Vamos (1993) concluded that peak mechanical power was the single best predictor of jump height ( $r = 0.93$ ). Others have reported a moderate correlation between VJP and average mechanical power ( $r = 0.71$ , Bosco & Komi 1979). It is clear, however, that when a single subject uses different jumping techniques, peak mechanical power during the jumps can vary significantly, while vertical jump performance (and external work done) remains constant (Bobbert et al. 1987a). This suggests that, while mechanical power is strongly correlated with, it is not necessarily a limiting factor of VJP.

Body mass (WEIGHT) was a major predictor of VJP differences among subjects: the greater the body mass, the lower the jump, even after taking into account peak mechanical power. This was not, of course, observed in the within-subject differences study, where the body mass was constant for each subject. NEGIMMAX, the peak negative impulse of BCOM, was a weak predictor of VJP differences between subjects, but it was a relevant factor in the within-subject study. This contradicts studies which have failed to obtain higher jumps when NEGIMMAX is increased by using "drop jumps" (Bobbert et al. 1987b). On the other hand, the result is in agreement with the supposed effect of NEGIMMAX on storage and utilization of elastic energy in muscles, which should result in higher jumps.

Both the time of propulsion (TPROP) and the amplitude of the movement (AMP) were significant predictors of VJP and TOVEL. Other things being equal, the longer the time a force is applied or the longer the distance over which a force is applied, the greater

the work done and, in this case, the higher the jump. In vertical jumping, there is a certain amount of flexion beyond which humans experience a decline in VJP, due to the mechanical properties of the musculotendinous units. Subjects do not seem, however, to exceed this limit.

It is apparent from hypotheses #3 and #4 that whole-body mechanics are excellent predictors of VJP. They provide, however, very limited information about the actual muscle actions which are producing the jump. Segmental analyses are necessary to understand the action of muscles on joints.

#### **Hypothesis 5.**

*At least 80% of the between-subjects variation (50% of the within-subjects variation) in VJP can be accounted for by a statistical model that includes muscular strength of the lower limbs and segmental kinematics and dynamics of the jump.*

The predictive ability of these segmental kinematics and dynamics was less than expected for both studies. The best models with between-subjects data accounted for about 60% of the VJP variation, while the best models using within-subjects data accounted for 34 to 51% of this variation. Given that an individual's variation in VJP is so small, the fact that an individual's VJP can be predicted at all using segmental kinematics and dynamics is, nevertheless, remarkable, showing that the relationships found are rather robust. Hypothesis #5 is rejected, concluding that statistical models including muscular strength of the lower limbs and segmental kinematics and dynamics of the jump can significantly predict VJP, but accounting for a smaller percentage of VJP variation than expected.

The between-subjects study showed that muscle performance characteristics were very important predictors of VJP. Muscular strength was relevant ( $r = 0.47$ ,  $p < 0.05$ ), but not as much as joint torques ( $r = 0.52$ ,  $p < 0.05$ ) or joint powers ( $r = 0.71$ ,  $p < 0.05$ ) during the execution of the jump. The second study showed that peak joint powers and peak joint torques were still relevant to VJP, even after controlling for "inherent" skeletal

muscle characteristics. This is a very important finding: skeletal muscles can and do develop different joint torques and powers during different trials of maximum vertical jumping, and these torques and powers are associated with different jump heights. Assuming that muscle activation is always maximum during maximum vertical jumping (Bobbert & van Ingen Schenau 1988, Pandy et al. 1990, Zajac et al. 1981)), it seems like coordination of the segmental actions during the vertical jump can have a strong influence on joint torque and power output; however, the coordination pattern responsible for this has not been identified so far.

Sequence of joint reversals was important for within-subject variation, but not for between-subjects variation in VJP. Within-subject differences in VJP were strongly associated with the sequence of joint reversals, where trials showing a HIP-ANKLE-KNEE sequence tended to result in higher jumps than those exhibiting the "ideal" HIP-KNEE-ANKLE sequence. Between-subject differences in VJP, however, had no significant relation with any coordination variables. It is possible that large between-subject differences in other variables obscured the relationship. No support was found for the theory that a proximal-to-distal sequence of joint reversals results in optimum vertical jump performance, but the hip joint reversal was virtually always the first one to occur.

Coordination of the segmental actions seems to have three main goals during maximum vertical jumping. If the word "coordination" is restricted to the appropriate timing of muscle activation which results in a particular timing of the actions of the segments, the first goal would be to ensure that skeletal muscles act under ideal conditions of contraction history, sarcomere length, and sarcomere shortening velocity, for maximum force development at high joint angular velocities. The second goal would be to optimize the segmental kinematics of the jump in order to achieve maximum vertical acceleration of the body center of mass. Finally, the third goal would be to optimize the position of the body center of mass at the instant of take-off. The arguments of Bobbert & van Ingen Schenau (1988), Hudson (1986), and Robertson & Fleming

(1987) for a proximal-to-distal sequence of joint reversals are based on goals two and three, but the ideal coordination strategy for maximum VJP would achieve the best combination of all three goals. This ideal coordination strategy has not been identified yet, but my data suggest that one of its essential elements is not necessarily a proximal-to-distal pattern of coordination, but a pattern where the hip joint reversal happens before the others.

The early reversal of hip motion may facilitate VJP based on a similar principle to the trigger mechanism in the locust kick. Heitler & Burrows (1977a, 1977b) proposed a motor program for the locust kick and jump where co-contraction of the strong extensors and the weak flexors happens in a position that locks the leg in place and allows for maximum tension development over a rather long period (500 ms); the tension is then released suddenly by a "trigger" mechanism which quickly suppresses the flexor activity. From my observations, it is possible that when HAT initiates extension before all other segments, its large mass combined with a positive vertical acceleration imposes a load on knee extensors and ankle plantar flexors. This load prevents the knee and especially the ankle from initiating extension in spite of the rising extensor torques. This should allow for a muscle tension buildup which would be otherwise impossible in dynamic conditions. The tension would then be quickly released when joint extension occurs. There is good evidence for a small additional knee flexion and ankle dorsiflexion after trunk extension starts (Hudson 1986, Pandy et al. 1990), which is in agreement with this proposition.

The identification of coordination strategies associated with vertical jump performance warrants further study. Future studies comparing subjects of different jumping abilities, as well as different trials within single subjects, should look into the role of joint reversal time difference between adjacent segments, as Hudson (1986) did. The timing of the peak joint torques and powers relative to the corresponding joint reversals should also be investigated. Finally, direct measures of the timing of muscle

activation would provide more accurate information on the actual motor control strategies, rather than on their mechanical consequences.

#### **Hypothesis 6.**

*Muscular strength of the lower limbs and segmental dynamics are able to explain more of the variation in vertical take-off velocity than segmental kinematics of the execution of the jump.*

The hypothesis is supported by the between-subjects study and by two out of three individuals from the within-subject study. Muscular strength and segmental dynamics accounted for 50% of the between-subject variation in TOVEL, while segmental kinematics could only account for 21%. The best models accounted for 59% vs 18% of TOVEL variation of the best jumper, and for 51% vs 16% in TOVEL variation of the worst jumper. The average jumper, however, gave the opposite results: segmental kinematics accounted for 31% while segmental dynamics only accounted for 24% of TOVEL variation. Although segmental dynamics are stronger predictors of TOVEL than segmental kinematics, the latter may be stronger in some subjects. The hypothesis is accepted.

#### **Hypothesis 7.**

*Segmental kinematics are able to explain more of the variation in the net vertical position of BCOM than muscular strength of the lower limbs and segmental dynamics of the execution of the jump.*

Data from both the between-subjects and the within-subjects studies showed no support for this hypothesis. None of the segmental kinematics predictors had a significant effect on between-subject variation in BCOMNET, while the best segmental dynamics models accounted for 35 to 40% of BCOMNET. Within-subjects results had the same tendency: segmental dynamics accounted for up to 50% of the variation in BCOMNET, in contrast with up to 22% of the variation accounted for by segmental kinematics. Hypothesis #7 is rejected.

### **Evaluation of models.**

The data from the studies in Chapters II and III can be used to evaluate both the theoretical model (Figure 2.2) and the within-subject differences statistical models. In Chapter II, overall statistical models were built using the relevant predictors from all levels of analysis. The fact that the best statistical models from each level in Table 2.6 could not be improved significantly by adding more variables from lower levels of analysis, together with the fact that no combination of predictors from different levels was better than the best models from the higher level alone, support the assumption that the best predictors from one level already include most of the information that could be provided by predictors from lower levels of analysis. This means that each level of analysis actually represents different levels of integration of information, with the lower levels providing more specific information about the physiological and anatomical bases of vertical jump performance.

The hypotheses tested several relationships among the different levels of the theoretical model (Figures 2.2 and 3.1). In the between subjects study (Table 2.6), the best models from level I were stronger predictors of VJP than the best models from level II, which were in turn stronger than the best models from levels III and IV. The same relationships held in the within-subject differences study (c.f. Tables 3.7 to 3.9), with the exception of level I where there were limitations in the accurate assessment of BCOMNET. It was also true that some predictors had a tendency to be more strongly associated with VJP than with TOVEL and vice versa. All of this information supports the theoretical model in Figures 2.2 and 3.1 as a reasonable approach to the study of vertical jumping.

Chapter III reports a best "summary" model from each level of analysis, developed from the best predictors of VJP for individual subjects (Tables 3.7 to 3.9). These summary models were tested on the remaining subjects for validation purposes (c.f. Table 3.10). It is also interesting to test these models (excluding trial number from

the predictors) on the data from the between-subject differences study, to verify whether the factors that are associated with changes in VJP from trial to trial can predict differences in VJP among subjects. The summary model from level I was identical to model 1 in Table 2.6 ( $VJP = k + tovel + bcomnet, R^2 = 0.95$ ). The summary model from level II was  $VJP = k - tprop + amp + amechp + peakpwr + negimmax, R^2 = 0.75$ . Average mechanical power and peak negative impulse were not statistically significant. The overall r-squared for this model is remarkably good, considering that WEIGHT was not included in the model. Finally, the best summary model from level III was  $VJP = k + hippwrmax + ankpwrmax - protodis, R^2 = 0.48$ . Neither peak ankle power nor the sequence of joint reversals were statistically significant. From this information, it is possible to say that the best statistical models from the within-subject differences study are good prediction models of the differences in VJP among subjects. The discrepancies on the significance of some of the predictors are probably due to the confounding effects of large differences of third variables among subjects.

### **Overall conclusions.**

These studies have identified several variables which are clearly associated with vertical jump performance. There was agreement, for the most part, between the relevant factors identified by the two studies presented. Whole-body kinematics and dynamics were strongly associated with VJP, especially peak mechanical power and average mechanical power, but they are somewhat limited in explaining the muscular actions involved in jumping. Joint kinematics and dynamics showed moderate associations with VJP. The strongest predictors were the peak joint powers and torques (particularly at the hip), and the sequence of joint reversals (but only for the within-subjects study). Muscle strength was significantly correlated with VJP, but peak joint torques and powers were stronger predictors. I found no evidence to support the theory that the ideal sequence of joint reversals is a proximal-to-distal sequence. Other coordination parameters (timing of the joint reversals, timing of the peak joint torques) were found to have no effect on VJP.

Among a group of individuals with different jumping abilities, the best jumpers had a lower body mass, larger peak joint powers and torques and a greater lower limb strength than the worst jumpers. They also developed greater whole-body peak and average mechanical power. Within single subjects, the best trials were characterized by the same performance variables, but a hip-ankle-knee sequence of joint reversals resulted in better jump results than the proximal-to-distal sequence.

In general, individuals were found to perform vertical jumps in a rather consistent way. Only a few variables, namely the timing of joint reversals and peak joint torques, and the peak angular accelerations during the negative phase, showed large variability from trial to trial. This means that not only actual vertical jump performance, but also the different characteristics of jumping, are reasonably well represented by taking the best jump from three or five trials.

The present results will prove useful in the design of future studies on training methods for improving VJP. Because of the role which I have confirmed that coordination plays in vertical jumping, future studies need to focus on the analysis of patterns of coordination and their relationship with VJP, and how these patterns of coordination are affected by training and practice. Single-subject research designs have proven useful for this, but the results may be clearer by artificially disturbing VJP in order to obtain a larger variation.

This study did not take into account the role that an armswing has in vertical jumping. Since vertical jumping with an armswing is closer to real-life jumping, it would be interesting to verify the conclusions from my study under that condition. Researchers interested in the role of the net take-off position of the body center of mass in within-subject differences in vertical jump performance, need to consider the greater accuracy which will be necessary to identify the relationships, because of the small variation in VJP and take-off position of BCOM.

### Notes to Chapter IV

<sup>1</sup>The average jumper from Chapter III had a range of BCOMNET of 100 mm, which included a potential maximal error of 19 mm (see Appendix C). Therefore, his true range could have been as low as 81 mm. For an ideal situation where measurement error does not exceed 10% of the true range of the variable, the error in measurement of BCOMNET should not be greater than 8 mm. Assuming that the main source of BCOMNET measurement error is an error in the identification of the instant of take-off, and assuming a constant take-off velocity of  $2.651 \text{ m} \cdot \text{s}^{-1}$ , the instant of take-off should be identified with an error no greater than 3.0 ms!

## **APPENDICES**

## APPENDIX A

### Calculation of Anthropometric Characteristics.

#### Center of mass of body segments.

The location of the center of mass of each segment was determined according to Vaughan et al. (1992), with the exception of HAT, which required special calculations.

The general equations are as follows:

$$xCOM_s = x_{\text{proximal joint}_s} + (ratio_s)(x_{\text{distal joint}_s} - x_{\text{proximal joint}_s}) \quad (\text{A.1})$$

$$zCOM_s = z_{\text{proximal joint}_s} + (ratio_s)(z_{\text{distal joint}_s} - z_{\text{proximal joint}_s}) \quad (\text{A.2})$$

where

$$ratio_{\text{HAT}} = 0.33$$

$$ratio_{\text{THI}} = 0.39$$

$$ratio_{\text{SHA}} = 0.42$$

$$ratio_{\text{FET}} = 0.44$$

#### Special calculations for HAT center of mass.

Calculation of the vertical position of the center of mass of the head, arms and trunk as a single segment (HAT) was derived from the data of Clauser et al. (1969) and its adjustments by Hinrichs (1990), assuming that when the subject is standing with arms akimbo, his arm and forearm form a 90-degree angle (Figure A.1).

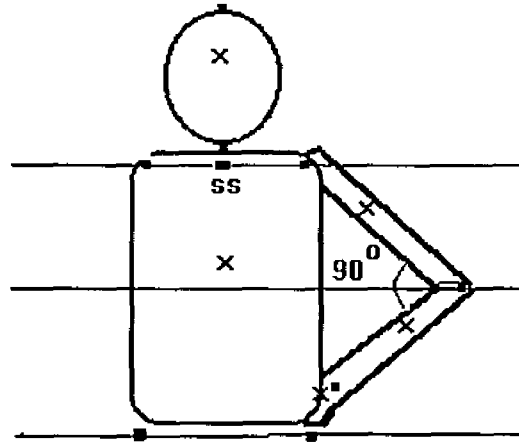


Fig. A.1: Segmental model used for calculation of HAT center of mass. *ss* = suprasternale.

**Table A.1.** Center of mass characteristics of segments comprising HAT.

Segment	COM (ratio) <sup>a</sup>	mass (% of body mass)	length (cm)
Head	0.47 <sup>b</sup>	07.3 <sup>b</sup>	31.67 <sup>b</sup>
Trunk	0.4383 <sup>c</sup>	50.7 <sup>b</sup>	50.24 <sup>c</sup>
Upper arm	0.4910 <sup>c</sup>	02.6 <sup>b</sup>	29.45 <sup>c</sup> * sin45 <sup>o</sup> <sup>d</sup>
Forearm	0.4176 <sup>c</sup>	01.6 <sup>b</sup>	27.13 <sup>c</sup> * sin45 <sup>o</sup> <sup>d</sup>

- (a) Ratio of distance from proximal end to distal end of segment.  
 (b) Clauser et al. (1969).  
 (c) Hinrichs' (1990) adjustments to data from Clauser et al., 1969.  
 (d) Multiplication by sine of 45° to adjust for position of the arms.

Relative masses of the segments and the vertical position of each segment relative to the reference point (*ss* in figure A.1 above) were used to calculate the center of mass of HAT. The location of  $COM_{HAT}$  was found using the equation:

$$z_{COM_{HAT}} = \frac{\sum_{i=1}^4 (\bar{x}length_i)(COMratio_i)(\%mass_i)}{\%mass_{HAT}} \quad (A.3)$$

where  $i = 1-4$  refers to the four segments that comprise HAT. This yields a ratio of 0.330 of trunk length for the HAT center of mass, relative to ss. This value is in good agreement with the ratio used by Winter (1990, p. 57).

### Center of mass of the whole body.

The center of mass (COM) locations of all the segments and their respective masses were used to calculate the whole body center of mass (BCOM), according to:

$$xBCOM = \sum_{s=1}^4 (xCOM_s)(mass_s)(mass_{body})^{-1} \quad (A.4)$$

$$zBCOM = \sum_{s=1}^4 (zCOM_s)(mass_s)(mass_{body})^{-1} \quad (A.5)$$

where  $mass_s$  is the mass of segment (s). Lower body segment masses were calculated based on the equations of Vaughan et al. (1992):

$$mass_{THI} = 2 [12.76 (\text{thigh length})(\text{midhigh circumference})^2 + 0.1032 (mass_{body}) - 1.023] \quad (A.6)$$

$$mass_{SHA} = 2 [31.33 (\text{shank length})(\text{calf circumference})^2 + 0.0226 (mass_{body}) + 0.016] \quad (A.7)$$

$$mass_{FET} = 2 [254.5 (\text{malleolus width})(\text{malleolus height})(\text{foot length}) + 0.0083 (mass_{body}) - 0.065] \quad (A.8)$$

The mass of head, arms, and trunk was calculated by subtraction:

$$mass_{HAT} = mass_{body} - (mass_{THI} + mass_{SHA} + mass_{FET}) \quad (A.9)$$

**Segmental moments of inertia.**

Moment of inertia for each segment about its center of mass was calculated according to Vaughan et al. (1992). Their formulae for the sagittal plane are as follows:

$$I_{O\ THI} = 2 \{ 0.00762 (\text{mass}_{\text{body}}) [(\text{thigh length})^2 + 0.076(\text{midthigh circumf})^2 ] \\ + 0.01153 \} \quad (\text{A.10})$$

$$I_{O\ SHA} = 2 \{ 0.00347 (\text{mass}_{\text{body}}) [(\text{shank length})^2 + 0.076(\text{calf circumf})^2 ] \\ + 0.00511 \} \quad (\text{A.11})$$

$$I_{O\ FET} = 2 \{ 0.00023 (\text{mass}_{\text{body}}) [ 4 (\text{malleolus height})^2 + 3 (\text{foot length})^2 ] \\ + 0.00022 \} \quad (\text{A.12})$$

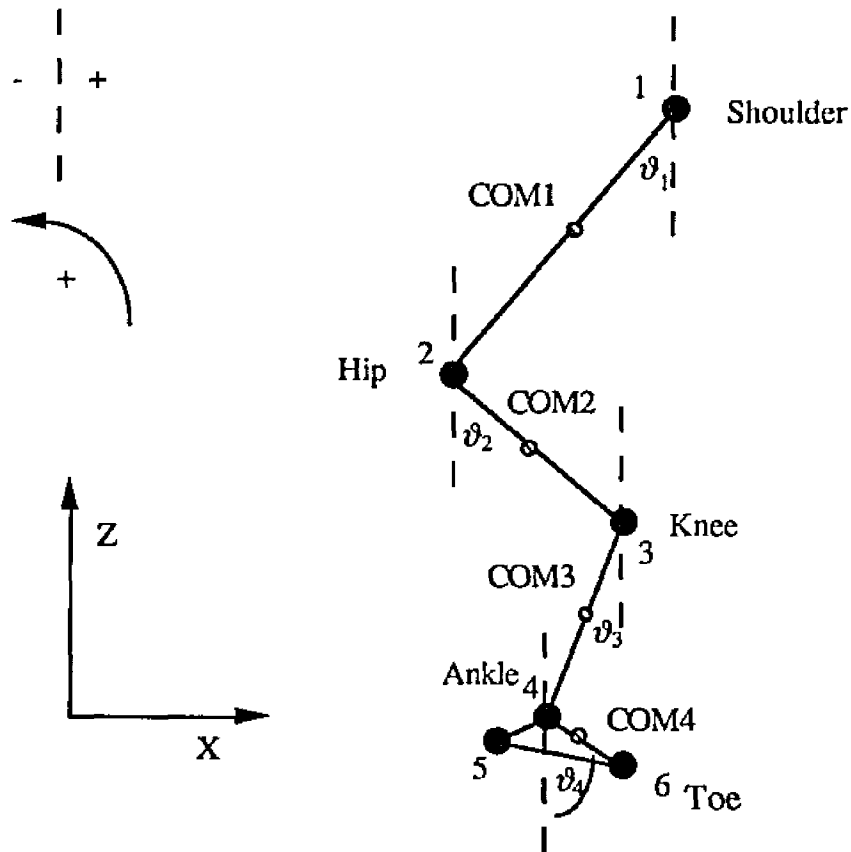
## APPENDIX B

### Biomechanical Model and Inverse Dynamics Calculations

This is a four-segment, unilateral, planar model. The segments are rigid, and are linked by frictionless, hinge joints.

#### Conventions

##### 1. Model and Sign Convention:



## 2. Notation:

Segment 1 = Head, arms, and trunk (HAT)

Segment 2 = Thighs (THI)

Segment 3 = Shanks (SHA)

Segment 4 = Feet (FET)

$\ddot{x}$ ,  $\ddot{z}$  = horizontal, vertical acceleration for the segment's center of mass

$\vartheta_i$  = angle for segment "i"

$\alpha_i$  = angular acceleration for segment "i"

COM<sub>i</sub> = Center of Mass for segment "i"

$m_i$  = mass for segment "i"

$I_i$  = moment of inertia about the center of mass for segment "i"

$g$  = acceleration due to gravity,  $9.81 \text{ m s}^{-2}$

$A_x$ ,  $A_z$  = ankle joint reaction force in the x, z directions

$K_x$ ,  $K_z$  = knee joint reaction forces in the x, z directions

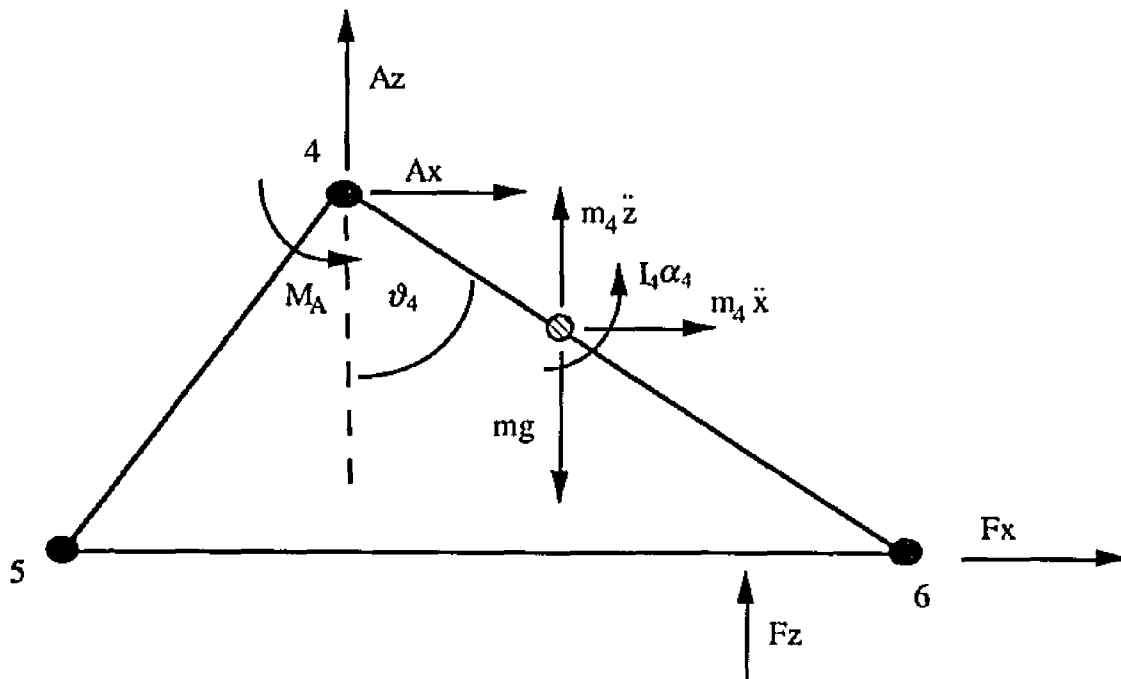
$H_x$ ,  $H_z$  = hip joint reaction forces in the x, z directions

$M_j$  = torque for joint "j"

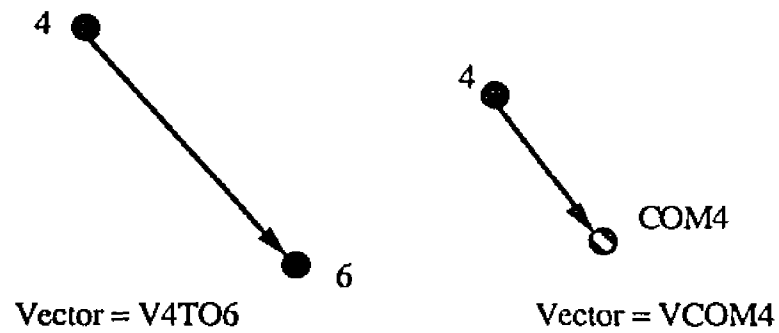
### Derivation of Equations of Motion

Equations of motion are derived using Newtonian mechanics. Calculations are made first for the foot, the distal segment. The external forces are known for the center of pressure of this segment. Calculations are then made for the proximal end of the segment, and then for the next adjacent segment.

#### a) Segment 4: The Foot



Vectors:



where

vector V4TO6 represents the toe position relative to the ankle  
 vector VCOM4 represents the center of mass of the foot relative to ankle  
 $V7 = V4 + VCOM4$   
 $b = COP_x - COM4_x$

Equations of motion for segment 4:

$$Ax = m_4 \ddot{x}_4 - Fx \quad (B.1)$$

$$Az = m_4 \ddot{z}_4 - Fz + m_4 g \quad (B.2)$$

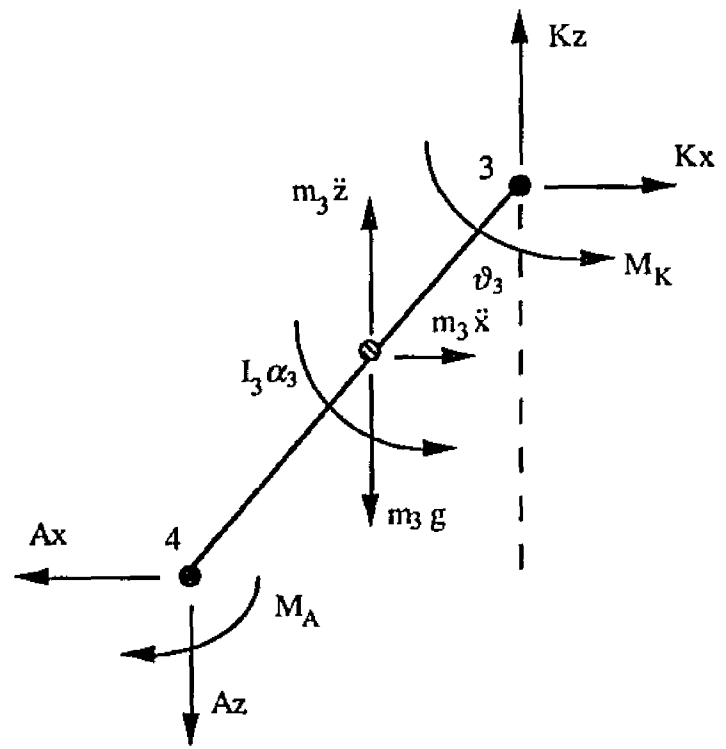
$$M_A = I_4 \alpha_4 - Fz(b) - Ax(VCOM4_x) - Az(-VCOM4_x) - Fx(V7_z) \quad (B.3)$$

Calculation of segment 4 angles:

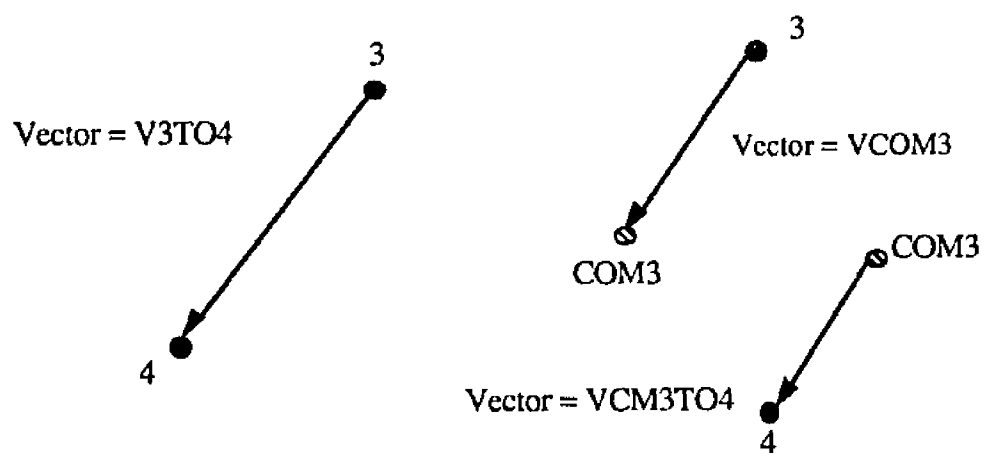
if  $V4TO6_x > 0$  and  $V4TO6_z < 0$  then

$$\vartheta_4 = \text{atan} \frac{V4TO6_x}{-(V4TO6_z)} \quad (B.4)$$

b) Segment 3: Shank



Vectors:



where

V3TO4 represents the ankle position relative to the knee  
 VCOM3 represents the center of mass of shank relative to the knee  
 VCM3TO4 represents the ankle position relative to shank COM

Equations of motion for segment 3:

$$Kx = m_3 \ddot{x}_3 + Ax \tag{B.5}$$

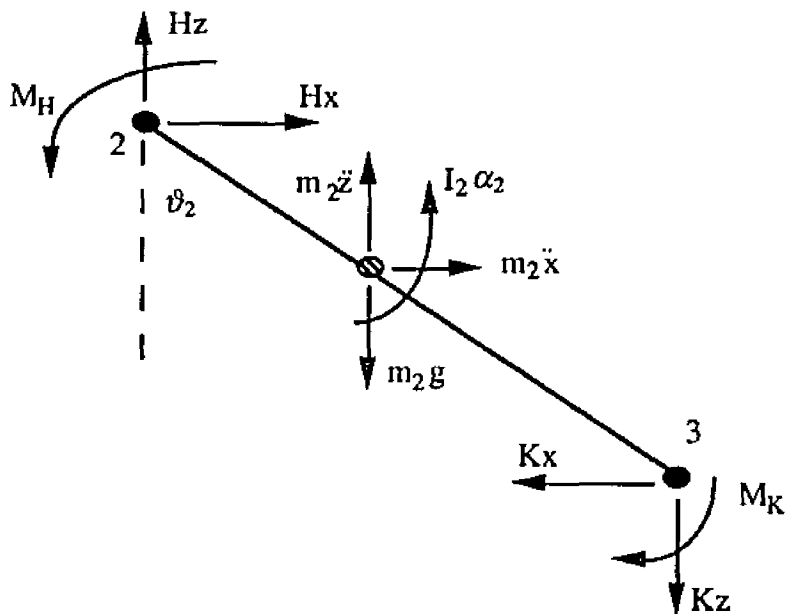
$$Kz = m_3 \ddot{z}_3 + m_3 g + Az \tag{B.6}$$

$$M_K = I_3 \alpha_3 + M_A - Ax(VCM3TO4z) + Az(VCM3TO4x) - Kx(VCOM3z) - Kz(-VCOM3x) \tag{B.7}$$

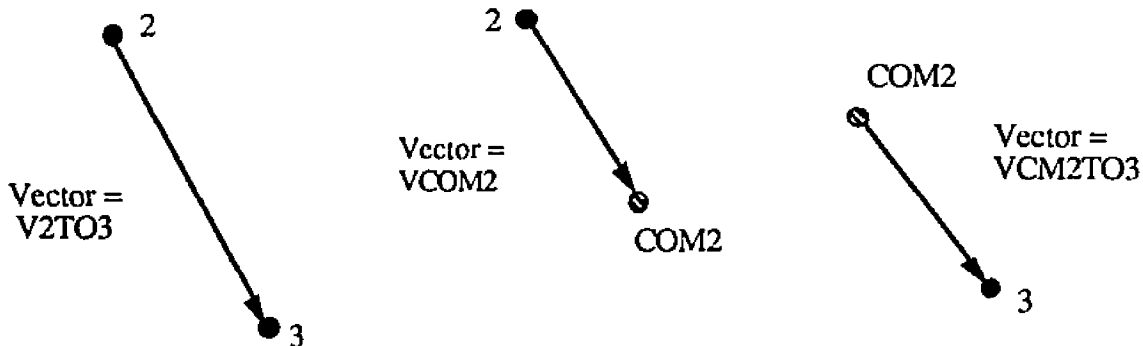
Calculation of segment 3 angles:

$$\vartheta_3 = \text{atan} \frac{V3TO4x}{-(V3TO4z)} \tag{B.8}$$

c) Segment 2: Thigh



Vectors:



where

V2TO3 represents the knee position relative to the hip  
 VCOM2 represents the center of mass of the thigh relative to the hip  
 VCM2TO3 represents the knee position relative to the thigh COM

*Equations:*

$$Hx = m_2 \ddot{x}_2 + Kx \quad (\text{B.9})$$

$$Hz = m_2 \ddot{z}_2 + m_2 g + Kz \quad (\text{B.10})$$

$$M_H = I_2 \alpha_2 + M_K - Kx(\text{VCM2TO3}_z) - Kz(-\text{VCM2TO3}_x) - Hx(\text{VCOM2}_z) - Hz(-\text{VCOM2}_x) \quad (\text{B.11})$$

*Calculations of segment 2 angle:*

$$\vartheta_2 = \text{atan} \frac{\text{V2TO3}_x}{-(\text{V2TO3}_z)} \quad (\text{B.12})$$

## APPENDIX C

### Assessment of Measurement Error

This section is concerned with the assessment of measurement error involved in the data collection and analysis for this dissertation. A certain amount of error is always present in empirical research. It is not possible to know exactly how much error is present and all its sources, but it is possible to detect some potential sources of error and assess its relative size.

#### Measurement error of the video system.

A static test was performed by placing a reflective golf ball in a fixed position at approximately 1.0 m from the floor. The data here represent 1.75 seconds of 60 Hz sampling from four cameras. Planar data from each one of the cameras were combined to create a single data set with 3-D position coordinates for the stationary golf ball, using exactly the same procedure and camera positions as for the dissertation data collection.

**Table C.1.** Descriptive statistics for golf ball test position data. Data are reported in centimeters. File: ball61.raw (unfiltered data). N = 105.

	X	Y	Z
Minimum	16.472	37.049	100.211
Maximum	16.553	37.331	100.236
Range	0.081	0.281	0.025
Mean	16.503	37.233	100.231
Median	16.500	37.243	100.233
Variance	0.001	0.003	0.000
Standard deviation	0.024	0.051	0.007
Standard error	0.002	0.005	0.001
Skewness	1.273	-1.341	-1.370
Kurtosis	0.303	4.357	0.676
Coeff. of variation	0.001	0.001	0.684 E-04

Minimal variation exists in the values, amounting to less than 1 millimeter. The largest variation is found in the Y axis, since the cameras were set up in such a way that

accuracy in the X and Z axes, which defined the sagittal plane for the jumpers, would be optimized.

It is also possible to verify the dynamic accuracy of the system by calculating the acceleration during the free fall of the golf ball, and comparing the result with the theoretical value of  $9.81 \text{ m} \cdot \text{sec}^{-2}$ . One trial (ball01.pat, a filtered data file) was used where the golf ball was dropped from 1.0 m unto the floor. The vertical path of the golf ball during free fall was differentiated twice (using finite differences), to obtain the instantaneous accelerations. A total of 44 sample points were used, which gave an average acceleration of  $-9.84 \text{ m} \cdot \text{sec}^{-2}$ , with a standard deviation of  $0.752 \text{ m} \cdot \text{sec}^{-2}$ . This variability is somewhat high (the acceleration ranged from  $-12.13 \text{ m} \cdot \text{sec}^{-2}$  to  $8.11 \text{ m} \cdot \text{sec}^{-2}$ ), but this is not uncommon of doubly-differentiated position data.

The accuracy of the video position data was, therefore, good; the acceleration data were slightly noisy. This is recognized, when pertinent, in the body of the dissertation.

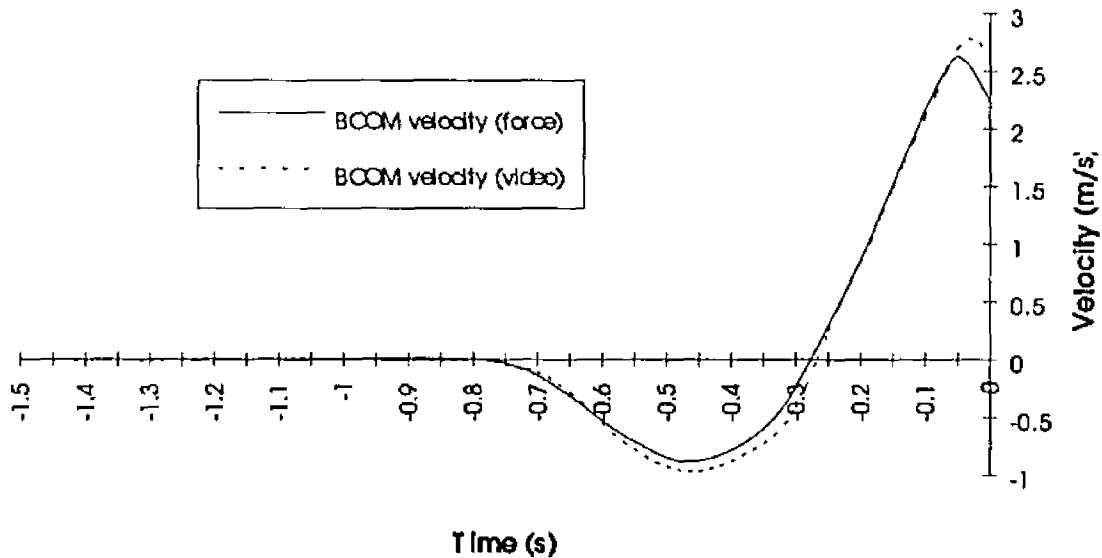
#### **Estimation of segmental centers of mass and moments of inertia.**

Among other potential sources for error, there is the estimation of the center of mass and moment of inertia of each body segment. These parameters cannot be measured accurately on living subjects in a practical, reasonable manner, and therefore need to be estimated from anthropometric measurements. Basic regression equations that use only body weight and height to predict the parameters are commonly used, but more accuracy is achieved when other particular anthropometric characteristics of each individual are taken into account (Vaughan et al. 1992). I have used the procedure developed by Vaughan et al. (1992)<sup>1</sup>, in an attempt to reduce this source of error to the minimum.

#### **Estimation of the whole-body center of mass.**

A useful comparison to verify the quality of the data is the comparison between the vertical velocity curves of the body center of mass, as obtained from video and from force data (see Bobbert & van Ingen Schenau 1988). Figure C.1 illustrates this comparison. The agreement is good, except for the extreme velocity values, indicating

that the biomechanical model used and the calculations performed are acceptable. The discrepancy is likely to originate from the artifact introduced by the differentiation process.



**Figure C.1.** Vertical velocity of the body center of mass vs time (trial di10t50). Time = 0 is the instant of take-off. The velocity obtained from the force record was calculated according to equation (9) in Chapter II. The velocity obtained from the video record was calculated by differentiation of the body center of mass position data (finite differences).

Because of the accuracy of the video system in measuring position data, and because of the procedures used to minimize the errors of calculation of the body center of mass, I have confidence in the accuracy of the whole body center of mass and segmental center of mass position data.

#### **Comparison of jump heights.**

One comparison that can be made to look at part of the methodological error involved in this study is the comparison between jump height as obtained directly from the maximum BCOM position in the video records (VJP, which is the criterion or, in validation language, the previously validated measure against which the new one will be tested), and the jump height obtained from integration of the vertical ground reaction force (JUMP2). The two calculations are theoretically equivalent, and the comparison

can show how accurately JUMP2 (and its two components, TOVEL and BCOMNET) are being measured. The calculations for VJP and JUMP2 are detailed in Chapter II, equations (7) and (8), respectively.

VJP and JUMP2 compare well for the between-subjects part of the dissertation. A paired t-test was performed on 52 subjects to check the null hypothesis that the mean difference between these two variables equals zero. The average difference was 1.5 cm (s.d. = 2.4 cm) which is statistically significant ( $p < 0.0005$ ). According to this test, I would reject the null hypothesis and conclude that the results of the calculations are different. However, the average difference (15 mm) is not biologically significant. A 95% confidence interval for the average difference is between -.0217 and -.0083 m, meaning that it is highly unlikely that the difference between the two measures could exceed 2.2 cm. This is rather small compared with the range of jump heights obtained (29.1 cm).

The validity of JUMP2 (and indirectly of TOVEL and BCOMNET) can be assessed by obtaining its coefficient of correlation with VJP. The two jump heights were strongly correlated:  $r = 0.952$ ,  $r^2 = 0.906$  ( $p < 0.0005$ ). This is an excellent validity coefficient.

This issue is more relevant for the within-subjects part of the dissertation, because the variation is small from trial to trial. If measurement error exceeded the variation in the dependent variable, there would be no basis for the analyses. The variation of VJP from jump to jump for each subject was, indeed, small, with a range of between 4 to 8 cm, depending on the subject. However, measurement error seems to be smaller. Table C.2 shows the 95% confidence intervals for the average difference ( $\Delta$ ) between VJP and JUMP2 for all eight subjects, as well as the validity of JUMP2 using VJP as the validation criterion. The maximum probable difference between these variables may be compared with the range of results obtained for VJP, for each subject. Finally, another way to estimate the error involved in measuring TOVEL and BCOMNET is by obtaining

an estimation of  $\sigma$ -hat, the error of each prediction model for VJP. This error is summarized in Table C.3 for the between-subjects study and for those subjects discussed in Chapter III.

**Table C.2.** Comparison between VJP and JUMP2 for each subject.  $\Delta$  is the average difference between the two variables, while "validity" refers to the coefficient of correlation between them.

Subject	95% C.I. for $\Delta$ (m)	VJP range (m)	Validity of JUMP2
DI10T (A)	-0.019 to -0.009	0.080	0.690
DI07T (B)	-0.010 to 0.004	0.055	0.549
DI09T (W)	-0.023 to -0.015	0.051	0.546
DI06T	-0.021 to -0.009	0.060	0.584
DI08T	-0.013 to -0.003	0.067	0.405
DI05T	-0.042 to -0.020	0.044	0.493
DI03T	-0.047 to -0.035	0.050	0.350
DI04T	-0.024 to -0.016	0.050	0.200 <sup>a</sup>

(a) This correlation coefficient is not statistically significant ( $p = 0.17$ ).

**Table C.3.** Estimation of measurement error for BCOMNET and TOVEL (combined).  $\sigma$ -hat is the square root of the Mean Square for Error.

Prediction model	MSE	$\sigma$ (mm)
Chapter II, Table 4, Model 1	.2783E-03	17
Chapter III, Table 5, Model 1	.8020E-04	9
Chapter III, Table 6, Model 1	.8166E-04	9
Chapter III, Table 7, Model 1	.5052E-04	7

It may be seen from Table C.2 that the difference between VJP and JUMP2 is about the same for this part of the study as it was for the between-subjects part above. Furthermore, the error involved in Model 1 for the between-subjects study was almost twice as large (Table C.3). The smaller coefficients of validity show, however, that the differences became more important when the variation in VJP became smaller. What is causing the discrepancy between VJP and JUMP2?

The calculation of JUMP2 involves the accurate calculation of both TOVEL and BCOMNET:

$$JUMP2 = \left[ (TOVEL)^2 * (2g)^{-1} \right] + z_{takeoff} BCOM - z_{standing} BCOM \quad (C.1)$$

An accurate calculation of both TOVEL and BCOMNET requires, in turn, an accurate determination of the instant of take-off. The instant of take-off was obtained from the force record, but BCOM position at take-off was obtained from the video data. Any synchronization error between force and video data potentially affects, therefore, the calculation of BCOMNET. Additional (but small) error in the calculation of both TOVEL and BCOMNET would also result from the error in determining the precise instant of take-off, due to the resolution of the video system (in this case, 60 Hz sampling).

With the system used for the present study<sup>2</sup>, it is possible to get up to one frame of synchronization error, because of the way the system is triggered: when the start trigger is issued, analog data acquisition starts immediately, but video acquisition must start at the beginning of a frame period. This may introduce a variable delay between 0 and 1 frames (0 to 0.0167 seconds), which is difficult to account for. An error of 0.0167 seconds in determining the instant of take-off would result in a BCOMNET error of approximately 4.4 cm!<sup>3</sup>

#### **Other sources of error.**

Many other sources of error are possible. The present discussion has focused on the sources of error that might affect the criterion of performance (VJP), and the two variables at level I of analysis (TOVEL and BCOMNET). Error may also be present in the measurement and calculation of all the other predictor variables. For example, in spite of careful standardization of the testing procedures, some individuals feel more comfortable using strength testing devices, and can perform closer to their true maximum. Careful calculations and procedures have been used to minimize these sources of error,

and results have been compared with other results in the literature. Whenever there is a concern about the accuracy of a particular variable, a comment has been included in the text. More detailed discussion of these sources of error is beyond the scope of this dissertation.

### Notes on Appendix C

<sup>1</sup>See Appendix A.

<sup>2</sup>Data acquired by four NEC TI-23A, CCD video cameras were processed and synchronized by a Motion Analysis VP320 video processor. The system was synchronized with the analog data acquisition from the force platform.

<sup>3</sup>This error is calculated assuming a constant velocity during that time equivalent to the average take-off velocity obtained in Chapter II:  $2.651 \text{ m} \cdot \text{s}^{-1}$ . The error would be greater or smaller depending on the take-off velocity of each particular subject.

## APPENDIX D

### Computer Code for Data Processing

*This computer code was written to be used with GX. GX is a non-compiled computer programming language that was developed by Greg Delozier at the Cleveland Clinic Foundation. GX is Public Domain material.*

```

; This is your super program Luis. God Bless You!
; LASPYM.GX 03-21-94
;
; Based on a primitive version by John Hahn
; Developed by Luis Aragon

; Built on laspyk.gx. This file is a slight modification of
; laspyk.gx for the processing of didata. The two major differences
; consist of 1) Automatically selecting tlowfrm after allowing me to
; check it on the screen, and reducing some "sleeps" to 1 second.
; 3-22-94. I will use this version, laspym.gx, for the remaining subjects
; after doing 7,9, 10, 6, and 4 with laspyk.gx.

'Go define
  Initialize
  Trials
end

'Initialize define
; "Enter the subject's height (m)" print input value 'bh :=
; "Enter the subject's thigh length (m)" print input value 'tl :=
; "Enter the subject's shank length (m)" print input value 'sl :=
; "Enter the subject's malleolus width (m)" print input value 'mw :=
; "Enter the subject's malleolus height (m)" print input value 'mh :=
; "Enter the subject's foot length (m)" print input value 'fl :=
; "Enter the subject's midthigh circumference(m)" print input value 'mtc :=
; "Enter the subject's calf circumference (m)" print input value 'cc :=
; "Enter empty force plate name without extension" print input 'NLname :=
; "Enter empty force plate trial number" print input value 'first :=
; "Enter force plate origin X component (m)" print input value 'FPOx :=
; "Enter standing reference name without extension" print input 'standref :=

```

```
; "Enter standing reference trial number" print input value 'refnum :=
; "Enter standing force plate reference name" print input 'fname :=
; "Enter standing force plate reference trial #" print input value 'tnum :=
; SUBJECT DI10T:
```

```
1.77 'bh :=
.458 't1 :=
.373 'sl :=
.070 'mw :=
.064 'mh :=
.256 'fl :=
.520 'mtc :=
.372 'cc :=
'ni10t 'NLname :=
1 'first :=
.194 'FPOx :=
'ri10t 'standref :=
1 'refnum :=
'ri10t 'fname :=
1 'tnum :=
```

```
Empty_Fplate
Anthropometrics
end
```

```
'Anthropometrics define
mw mh * fl * 254.5 * 't1 :=
bm 0.0083 * 0.065 - 't2 :=
t1 t2 + 2 * 'seg4_m :=
cc cc * sl * 31.33 * 't1 :=
bm 0.0226 * 0.016 + 't2 :=
t1 t2 + 2 * 'seg3_m :=
mtc mtc * t1 * 12.76 * 't1 :=
0.1032 bm * 1.023 - 't2 :=
t1 t2 + 2 * 'seg2_m :=
seg4_m seg3_m + seg2_m + 't1 :=
bm t1 - 'seg1_m :=
```

```
; Calculating Moments of Inertia
mtc mtc * 0.076 * 't1 :=
t1 t1 * t1 + 't2 :=
t2 bm * 0.00762 * 0.01153 + 't3 :=
t3 2 * 'Ith :=

cc cc * 0.076 * 't1 :=
```

```

sl sl * t1 + 't2 :=
t2 bm * 0.00347 * 0.00511 + 't3 :=
t3 2 * 'Ish :=

fl fl * 3 * 't1 :=
mh mh * 4 * t1 + 't2 :=
t2 bm * 0.00023 * 0.00022 + 't3 :=
t3 2 * 'Ift :=
't1 discard 't2 discard 't3 discard 't1 discard 'sl discard
'mw discard 'mh discard 'fl discard 'mtc discard 'cc discard

```

COM\_Standing

end

```

'COM_Standing define
refnum 'first :=
standref specialk '.pat + ' cload
Path_Data
'VCOM2x discard 'VCOM2z discard 'VCOM3x discard 'VCOM3z discard
'VCOM4x discard 'VCOM4z discard 'THIvd discard 'SHAvd discard
'FETvd discard 'VCM3TO4x discard 'VCM3TO4z discard
'VCM2TO3x discard 'VCM3TO4z discard
empty
"Hi dude" print
COM
graphics
BCOMz 1 vp hcursor
text
empty
"Enter standing COM in z direction (m)" print input value 'BCOMst :=
'BCOMz discard 'BCOMx discard
empty
end

```

```

'Empty_Fplate define
NLname specialk '.ts + ' load
call sp
"Calibration is complete... This is really working!" print
mat1 1 c 'F1x :=
mat1 3 c 'F1z :=
mat1 5 c 'M1y :=
mat1 6 c 'M1z :=
'mat1 discard
F1x average 'F1x0 :=

```

```

F1z average 'F1z0 :=
M1y average 'M1y0 :=
M1z average 'M1z0 :=
'F1x discard 'F1z discard 'M1y discard 'M1z discard
fname tnum+ '.ts + ' load
callsp
"calibration complete" print
mat1 3 c 'F1Z :=
F1Z F1z0 - 'F1Z :=
'mat1 discard
F1Z 1 10 rs average 'FZ :=
FZ 9.81 /
.
l sleep
"Enter the reference body mass" print input value 'bm :=
'F1Z discard
empty
end

```

'Trials define

```

"Enter the number of jump types" print input value 'njs :=
l 'try :=
while try njs <= do
  "Doing jump type #" print try .
  "Enter file name without extension" print input 'tft :=
  "Enter first trial number" print input value 'trial1 :=
  "Enter last trial number" print input value 'last :=

  while trial1 last <= do
    "Doing jump type" print try .
    "Doing trial #" print trial1 .
    "Enter first frame" print input value 'f1 :=
    "Enter last frame" print input value 'ff :=
    trial1 'first :=
    tft specialk '.pat + ' cload
    Path_Data
    COM
    Angles
    tft specialk '.ts + ' load
    Force_Data
    Numbers
    Takeoff_Vel
    COP
    Torques
    MISC
  
```

```

        Save_Files
        trial1 1 + 'trial1 :=
    endwhile
    try 1 + 'try :=
endwhile
end

'Path_Data define
    "Calculating path data, Luis" print .
;   VCOM indicates a vector along the segment (tail at proximal
;   joint, head at COM of the segment). VCM indicates a vector from
;   the laboratory origin to the COM of the segment.
;
; Loading in the path data
    shoulder 100 / 'RT_Shoulder :=
    RT_HIP 100 / 'RT_Hip :=
    RT_Knee 100 / 'RT_Knee :=
    RT_Ankle 100 / 'RT_Ankle :=
    RT_Met 100 / 'RT_Met :=
    'shoulder discard 'RT_HIP discard

; Splitting the path data into x and z components.
    RT_Ankle 1 c 'RT_Anklex :=
    RT_Ankle 3 c 'RT_Anklez :=
    'RT_Ankle discard
    RT_Knee 1 c 'RT_Kneex :=
    RT_Knee 3 c 'RT_Kneez :=
    'RT_Knee discard
    RT_Hip 1 c 'RT_Hipx :=
    RT_Hip 3 c 'RT_Hipz :=
    'RT_Hip discard
    RT_Shoulder 1 c 'RT_Shoulderx :=
    RT_Shoulder 3 c 'RT_Shoulderz :=
    'RT_Shoulder discard
    RT_Met 1 c 'RT_Metx :=
    RT_Met 3 c 'RT_Metz :=
    'RT_Met discard

; Calculating the VCOMs for each segment. These will be used for
; angle calculations and for VCM calculations.
    RT_Hipx RT_Shoulderx - 0.33 * 'VCOM1x :=
    RT_Hipz RT_Shoulderz - 0.33 * 'VCOM1z :=
    RT_Kneex RT_Hipx - 0.39 * 'VCOM2x :=
    RT_Kneez RT_Hipz - 0.39 * 'VCOM2z :=
    RT_Anklex RT_Kneex - 0.42 * 'VCOM3x :=

```

```

RT_Anklez RT_Kneez - 0.42 * 'VCOM3z :=
RT_Metx RT_Anklex - 0.44 * 'VCOM4x :=
RT_Metz RT_Anklez - 0.44 * 'VCOM4z :=

```

```

; Calculating the VCMs for each segment.

```

```

RT_Anklex VCOM4x + 'VCM4x :=
RT_Anklez VCOM4z + 'VCM4z :=
RT_Kneex VCOM3x + 'VCM3x :=
RT_Kneez VCOM3z + 'VCM3z :=
RT_Hipx VCOM2x + 'VCM2x :=
RT_Hipz VCOM2z + 'VCM2z :=
RT_Shoulderx VCOM1x + 'VCM1x :=
RT_Shoulderz VCOM1z + 'VCM1z :=

```

```

; Calculating Moment Arms

```

```

RT_Anklez VCOM4z + 'V7 :=
RT_Anklex VCM3x - 'VCM3TO4x :=
RT_Anklez VCM3z - 'VCM3TO4z :=
RT_Kneex VCM2x - 'VCM2TO3x :=
RT_Kneez VCM2z - 'VCM2TO3z :=

```

```

RT_Metx RT_Anklex - 'V4TO6x :=
RT_Metz RT_Anklez - 'V4TO6z :=
RT_Anklex RT_Kneex - 'V3TO4x :=
RT_Anklez RT_Kneez - 'V3TO4z :=
RT_Kneex RT_Hipx - 'V2TO3x :=
RT_Kneez RT_Hipz - 'V2TO3z :=

```

```

; Calculating velocity differences between proximal and distal
; joints at each segment.

```

```

RT_Shoulderz deriv 60 * 'RT_Shoulderzv :=
RT_Hipz deriv 60 * 'RT_Hipzv :=
RT_Kneez deriv 60 * 'RT_Kneezv :=
RT_Anklez deriv 60 * 'RT_Anklezv :=
RT_Metz deriv 60 * 'RT_Metzv :=

```

```

RT_Shoulderzv RT_Hipzv - 'HATvd :=
RT_Hipzv RT_Kneezv - 'THIvd :=
RT_Kneezv RT_Anklezv - 'SHAvd :=
RT_Anklezv RT_Metzv - 'FETvd :=

```

```

'RT_Shoulderzv discard 'RT_Hipzv discard 'RT_Kneezv discard
'RT_Metzv discard

```

```

; Cleaning up the memory
  'RT_Shoulderx discard 'RT_Shoulderz discard
  'RT_Hipx discard 'RT_Hipz discard 'RT_Kneex discard
  'RT_Kneez discard 'RT_Anklex discard 'RT_Anklez discard
  'RT_Metx discard 'RT_Metz discard
  empty

  end

'COM define
  "Calculating the body COM Luis, God loves you!" print
  VCM1z seg1_m * 't1 :=
  VCM2z seg2_m * 't2 :=
  VCM3z seg3_m * 't3 :=
  VCM4z seg4_m * 't4 :=
  t1 t2 + t3 + t4 + 't5 :=
  t5 bm / 'BCOMz :=

  VCM1x seg1_m * 't1 :=
  VCM2x seg2_m * 't2 :=
  VCM3x seg3_m * 't3 :=
  VCM4x seg4_m * 't4 :=
  t1 t2 + t3 + t4 + 't5 :=
  t5 bm / 'BCOMx :=

  't1 discard 't2 discard 't3 discard 't4 discard 't5 discard
  empty

  end

'Angles define
  "Calculating angles" print
  VCOM1z recip 'VCOM1zr :=
  VCOM1x VCOM1zr scale atan 'theta1 :=
  VCOM2z recip 'VCOM2zr :=
  VCOM2x VCOM2zr scale atan 'theta2 :=
  VCOM3z recip 'VCOM3zr :=
  VCOM3x VCOM3zr scale atan 'theta3 :=
  VCOM4z recip 'VCOM4zr :=
  VCOM4x VCOM4zr scale atan 'theta4 :=

  3.1415927 'pi :=
  theta1 theta2 - 't1 :=
  t1 abs 't2 :=
  t2 -1 * pi + 'rHip_Angle :=

```

```

theta2 theta3 - pi + 'rKnee_Angle :=
theta4 abs 't1 :=
theta4 theta3 - 't2 :=
t2 pi + 'rAnkle_Angle :=
'theta1 discard 'theta2 discard 'theta3 discard 'theta4 discard
't1 discard 't2 discard
empty

```

; Calculating the relative angular velocities and angular accelerations of  
; the hip, knee, and ankle.

```

rHip_Angle deriv 60 * 'rHip_aVel :=
rHip_aVel deriv 60 * 'rHip_aAcc :=
rKnee_Angle deriv 60 * 'rKnee_aVel :=
rKnee_aVel deriv 60 * 'rKnee_aAcc :=
rAnkle_Angle deriv 60 * 'rAnkle_aVel :=
rAnkle_aVel deriv 60 * 'rAnkle_aAcc :=

end

```

```

'Force_Data define
  "Calculating the force data" print
  callsp
  "calibration complete" print
  mat1 1 c 'F1X :=
  mat1 3 c 'F1Z :=
  mat1 5 c 'M1Y :=
  mat1 6 c 'M1Z :=

  F1X F1x0 - 'F1X :=
  F1Z F1z0 - 'F1Z :=
  M1Y M1y0 - 'M1Y :=
  M1Z M1z0 - 'M1Z :=
  'mat1 discard

; Synchronizing the force files with the video files, according to the
; suspected timing error of the system of 0.03311 seconds, or ÷ 10 frames.
  F1X 11 1195 rs 'F1X :=
  F1Z 11 1195 rs 'F1Z :=
  M1Y 11 1195 rs 'M1Y :=

; Cutting the 300Hz force files down to 60Hz to match the video data.
; I tag a little "v" on the end of the name to indicate force data that
; matches video.
  1185 sequence F1X spline 237 sequence 236 / 1184 * splint 'F1Xv :=
  1185 sequence F1Z spline 237 sequence 236 / 1184 * splint 'F1Zv :=
  1185 sequence M1Y spline 237 sequence 236 / 1184 * splint 'M1Yv :=
  'F1X discard 'M1Y discard

; Taking out the relevant parts of the force data-i.e., when you tracked
; the video data, you cut, using only a portion of the 4 seconds. We need
; that same portion for the force.
  F1Xv f1 ff rs 'F1XV :=
  F1Zv f1 ff rs 'F1ZV :=
  M1Yv f1 ff rs 'M1YV :=
  'F1Xv discard 'F1Zv discard 'M1Yv discard
  empty

  end

'Numbers define
  cls
  "Now we find the takeoff and minimum COM locations, Luis" print
  2 sleep
  graphics

```

```

F1Z 1 vp hcursor
text
"Enter the location of takeoff3 (frame #)" print input value 'takeoff3 :=
takeoff3 1 - 5 / 1 + 'takeoff :=
takeoff .
2 sleep
BCOMz minrc drop 'COMm := drop
graphics
BCOMz 1 vp hcursor
text
"Enter YES to accept the default value, NO to fix it" print input 'accept :=
if accept 'no = then "Enter the replacement frame# for lowest position" print input
value 'COMm := endif
COMm .
1 sleep

end

'Takeoff_Vel define
cls
"Calculating the takeoff velocity of the COM of the body" print

; This is the calculation using 60HZ force records.
F1ZV f1 takeoff rs 'F1ZmV :=
F1ZmV FZ - 'FZZ :=
FZZ integ 60 / 'Fdt :=
Fdt bm / 'TOvel :=

; And this is the calculation using the 300Hz force records.
F1Z 1 takeoff3 rs 'F1Zm :=
F1Zm FZ - 'FZZ :=
FZZ integ 300 / 'Fdt :=
Fdt bm / 'zCOMvel :=
'bmm discard 'Fdt discard 'FZZ discard
empty
end

'acc define
deriv deriv 60 * 60 *
end

'COP define
F1ZV recip 'F1Zr :=
M1YV F1Zr * FPOx + 'COPx :=
'M1YV discard 'F1Zr discard

```

```
; Calculating b, the moment arm for the vertical force applied at
; the foot.
```

```
  COPx VCM4x - 'b :=
```

```
  end
```

```
'Torques define
```

```
  cls
```

```
  "Calculating the torques" print
```

```
; Calculating the absolute angles.
```

```
; The ankle.
```

```
  1 .
```

```
  V4TO6z -1 * 'V4TO6zn :=
```

```
  V4TO6zn recip 'V4TO6znr :=
```

```
  V4TO6x V4TO6znr scale atan 'Ankle_Angle :=
```

```
; The knee.
```

```
  2 .
```

```
  V3TO4z -1 * 'V3TO4zn :=
```

```
  V3TO4zn recip 'V3TO4znr :=
```

```
  V3TO4x V3TO4znr scale atan 'Knee_Angle :=
```

```
; The hip.
```

```
  3 .
```

```
  V2TO3z -1 * 'V2TO3zn :=
```

```
  V2TO3zn recip 'V2TO3znr :=
```

```
  V2TO3x V2TO3znr scale atan 'Hip_Angle :=
```

```
'V4TO6x discard 'V4TO6z discard 'V4TO6zn discard
```

```
'V3TO4z discard 'V3TO4x discard 'V3TO4zn discard
```

```
'V2TO3z discard 'V2TO3x discard 'V2TO3zn discard
```

```
empty
```

```
; Calculating the angular accelerations of the
```

```
; absolute angles.
```

```
  Ankle_Angle deriv deriv 60 * 60 * 'Ankle_aAcc :=
```

```
  Hip_Angle deriv deriv 60 * 60 * 'Hip_aAcc :=
```

```
  Knee_Angle deriv deriv 60 * 60 * 'Knee_aAcc :=
```

```
; Ankle torque (Ma)
```

```
  "Doing the ankle" print
```

```
  VCM4x acc 'VCM4xa :=
```

VCM4z acc 'VCM4za :=

VCM4xa seg4\_m \* F1XV - 'Ax :=

VCM4za seg4\_m \* F1ZV - 't1 :=

seg4\_m 9.81 \* 'shta :=

t1 shta + 'Az :=

'VCM4xa discard 'VCM4za discard 't1 discard 'VCM4x discard 'VCM4z discard  
'shta discard

"Getting there..." print

Ankle\_aAcc Ift \* 't1 :=

F1ZV b \* 't2 :=

t1 t2 + 't3 :=

VCOM4x Az \* 't4 :=

VCOM4z Ax \* 't5 :=

V7 F1XV \* 't6 :=

t1 t2 - t5 - t4 + t6 - 'Ma :=

'F1XV discard 'V7 discard 'VCOM4x discard 'VCOM4z discard 'b discard  
't1 discard 't2 discard 't3 discard 't4 discard 't5 discard 't6 discard  
empty

; Knee torque (Mk)

"Doing the knee" print

VCM3x acc 'VCM3xa :=

VCM3z acc 'VCM3za :=

VCM3xa seg3\_m \* Ax + 'Kx :=

VCM3za seg3\_m \* Az + 't1 :=

seg3\_m 9.81 \* 'shtk :=

t1 shtk + 'Kz :=

'VCM3xa discard 'VCM3za discard 'shtk discard

Ish Knee\_aAcc \* Ma + 't1 :=

VCM3TO4z Ax \* -1 \* t1 + 't2 :=

VCM3TO4x Az \* t2 + 't3 :=

VCOM3z Kx \* -1 \* t3 + 't4 :=

VCOM3x Kz \* t4 + 'Mk :=

'VCM3x discard 'VCM3z discard 'VCM3TO4x discard  
'VCM3TO4z discard 't1 discard 't2 discard 't3 discard  
't4 discard 'Ax discard 'Az discard  
empty

```

; Hip torque (Mh)
  "Doing the hip" print
  VCM2x acc 'VCM2xa :=
  VCM2z acc 'VCM2za :=

  VCM2xa seg2_m * Kx + 'Hx :=
  VCM2za seg2_m * Kz + 't1 :=
  seg2_m 9.81 * 'shth :=
  t1 shth + 'Hz :=

  "A ver que pasa" print
  Hip_aAcc lth * Mk + 't1 :=
  Kx VCM2TO3z * -1 * t1 + 't2 :=
  Kz VCM2TO3x * t2 + 't3 :=
  Hx VCOM2z * -1 * t3 + 't4 :=
  Hz VCOM2x * t4 + 'Mh :=

;   Fitting the torques to my particular convention
  Ma -1 * 'Ma :=
  Mh -1 * 'Mh :=

  'VCM2xa discard 'VCM2za discard 'VCM2x discard 'VCM2z discard
  'Hx discard 'Hz discard 'Kx discard 'Kz discard
  'VCM2TO3x discard 'VCM2TO3z discard 't1 discard 't2 discard
  't3 discard 't4 discard
  empty

end

'MISC define
  "Doing the loose ends" print

; Calculating total body power.
  1 .
  F1Zm zCOMvel * 'TBP3 :=

; Calculating jump height.
  2 .
  zCOMvel takeoff3 r 'TV :=
  BCOMz takeoff r 'BCOMto :=
  TV TV * 2 / 9.81 / 't1 :=
  BCOMto t1 + BCOMst - 'BCOMpeak :=

```

; Calculating net vertical position of the body at takeoff.

```
3 .
  BCOMto BCOMst - 'BCOMnet :=
```

; Calculating hip, knee, and ankle angles at takeoff.

```
4 .
  rHip_Angle takeoff 1 rc 'rHip_A_to :=
  rKnee_Angle takeoff 1 rc 'rKnee_A_to :=
  rAnkle_Angle takeoff 1 rc 'rAnkle_A_to :=
```

; Calculating time of propulsion.

```
5 .
  takeoff 60 / 'to :=
  COMm 60 / 'tlow :=
  to tlow - 'tprop :=
```

; Calculating average vertical acceleration of the COM.

```
6 .
  TV tprop / 'AVA :=
```

; Calculating the amplitude of the movement.

```
7 .
  BCOMz COMm r 'BCOMlow :=
  BCOMto BCOMlow - 't1 :=
  t1 bh / 100 * 'AMP :=
  't1 discard
```

; Calculating average mechanical power.

```
8 .
  BCOMz max 'BCOMzmax :=
  BCOMlow BCOMzmax - 't1 :=
  t1 bm * -9.81 * tprop / 'A_MechP :=
```

; Calculating peak mechanical power.

```
9 .
  TBP3 max 'TBP3max :=
```

; Calculating joint powers and peak joint powers.

```
10 .
  Mh rHip_aVel * 'hpwr :=
  hpwr fl takeoff rs 'hpwrshort :=
  hpwrshort max 'hpwrmax :=
  hpwrshort maxrc drop 'hpwrmax# := drop
  "Find peak hip power." print
  1 sleep
```

```

graphics
hpwrshort 1 vp hcursor
text
"Enter YES to accept the default value, NO to fix it" print input 'accept :=
if accept 'no = then "Enter the substitution value for peak hip power" print input
value 'hpwrmax := endif
if accept 'no = then "Enter the replacement frame# for peak hip power" print input
value 'hpwrmax# := endif
Mk rKnee_aVel * 'kpwr :=
kpwr fl takeoff rs 'kpwrshort :=
kpwrshort max 'kpwrmax :=
kpwrshort maxrc drop 'kpwrmax# := drop
"Find peak knee power." print
1 sleep
graphics
kpwrshort 1 vp hcursor
text
"Enter YES to accept the default value, NO to fix it" print input 'accept :=
if accept 'no = then "Enter the substitution value for peak knee power" print input
value 'kpwrmax := endif
if accept 'no = then "Enter the replacement frame# for peak knee power" print input
value 'kpwrmax# := endif
Ma rAnkle_aVel * 'apwr :=
apwr fl takeoff rs 'apwrshort :=
apwrshort max 'apwrmax :=
apwrshort maxrc drop 'apwrmax# := drop
"Find peak ankle power." print
1 sleep
graphics
apwrshort 1 vp hcursor
text
"Enter YES to accept the default value, NO to fix it" print input 'accept :=
if accept 'no = then "Enter the substitution value for peak ankle power" print input
value 'apwrmax := endif
if accept 'no = then "Enter the replacement frame# for peak ankle power" print input
value 'apwrmax# := endif
'hpwrshort discard 'kpwrshort discard 'apwrshort discard

```

```

; Calculating peak hip, knee, and ankle net torques and the times when
; they occur.

```

```

empty
cls
Mh fl takeoff rs 'Mhshort :=
Mhshort max 'mMh :=
Mhshort maxrc drop 'Mhf := drop

```

```

"Find max hip torque and when it occurs." print
1 sleep
graphics
Mh 1 vp hcursor
Mhshort 2 vp hcursor
text
"Enter YES to accept the default value, NO to fix it" print input 'accept :=
if accept 'no = then "Enter the replacement value for peak hip torque" print input
value 'mMh := endif
if accept 'no = then "Enter the replacement frame# for peak hip torque" print input
value 'Mhf := endif
Mhf 60 / 'Mht :=
Mk f1 takeoff rs 'Mkshort :=
Mkshort max 'mMk :=
Mkshort maxrc drop 'Mkf := drop
"Find max knee torque and when it occurs." print
1 sleep
graphics
Mk 1 vp hcursor
Mkshort 2 vp hcursor
text
"Enter YES to accept the default value, NO to fix it" print input 'accept :=
if accept 'no = then "Enter the replacement value for peak knee torque" print input
value 'mMk := endif
if accept 'no = then "Enter the replacement frame# for peak knee torque" print input
value 'Mkf := endif
Mkf 60 / 'Mkt :=
Ma f1 takeoff rs 'Mashort :=
Mashort max 'mMa :=
Mashort maxrc drop 'Maf := drop
"Find max ankle torque and when it occurs." print
1 sleep
graphics
Ma 1 vp hcursor
Mashort 2 vp hcursor
text
"Enter YES to accept the default value, NO to fix it" print input 'accept :=
if accept 'no = then "Enter the replacement value for peak ankle torque" print input
value 'mMa := endif
if accept 'no = then "Enter the replacement frame# for peak ankle torque" print input
value 'Maf := endif
Maf 60 / 'Mat :=

'Mhshort discard 'Mkshort discard 'Mashort discard

```

```

; Calculating joint reversal times.
  empty
  rHip_Angle f1 takeoff rs 'rHip_Anshrt :=
  rHip_Anshrt minrc drop 'Hipjvf := drop
  "Find frame # of hip reversal time." print
  1 sleep
  graphics
  rHip_Angle 1 vp hcursor
  rHip_Anshrt 2 vp hcursor
  text
  "Enter YES to accept the default value, NO to fix it" print input 'accept :=
  if accept 'no = then "Enter the replacement frame# for hip joint reversal" print input
value 'Hipjvf := endif
  Hipjvf 60 / 'Hipjvt :=
  rKnee_Angle f1 takeoff rs 'rKne_Anshrt :=
  rKne_Anshrt minrc drop 'Kneejvf := drop
  "Find frame # of knee reversal time." print
  1 sleep
  graphics
  rKnee_Angle 1 vp hcursor
  rKne_Anshrt 2 vp hcursor
  text
  "Enter YES to accept the default value, NO to fix it" print input 'accept :=
  if accept 'no = then "Enter the replacement frame# for knee joint reversal" print input
value 'Kneejvf := endif
  Kneejvf 60 / 'Kneejvt :=
  rAnkle_Angle f1 takeoff rs 'rAnk_Anshrt :=
  rAnk_Anshrt minrc drop 'Anklejvf := drop
  "Find frame # of ankle joint reversal." print
  1 sleep
  graphics
  rAnkle_Angle 1 vp hcursor
  rAnk_Anshrt 2 vp hcursor
  text
  "Enter YES to accept the default value, NO to fix it" print input 'accept :=
  if accept 'no = then "Enter the replacement frame# for ankle joint reversal" print
input value 'Anklejvf := endif
  Anklejvf 60 / 'Anklejvt :=
  'rHip_Anshrt discard 'rKne_Anshrt discard 'rAnk_Anshrt discard

; Calculating net torques at time of joint reversal.
  Mh Hipjvf 1 rc 'Mhjvt :=
  Mk Kneejvf 1 rc 'Mkjvt :=
  Ma Anklejvf 1 rc 'Majvt :=

```

```

; Calculating the time difference between the first and last peak net
; joint torques.
  { Mht Mkt Mat } 'matriz :=
  matriz max 'm1 :=
  matriz min 'm2 :=
  m1 m2 - 'mMtdiff :=
  'm1 discard 'm2 discard

; Calculating time of occurrence of the peak velocity differences
; between proximal and distal joint segments.
  HATvd f1 takeoff rs 'HATvdshort :=
  HATvdshort maxrc drop 'fHAT := drop
  "Find the frame # of peak velocity differences." print
  1 sleep
  graphics
  HATvd 1 vp hcursor
  HATvdshort 2 vp hcursor
  text
  "Enter YES to accept the default value, NO to fix it" print input 'accept :=
  if accept 'no = then "Enter the HATvd frame # replacement" print input value 'fHAT
:= endif
  THIVd f1 takeoff rs 'THIVdshort :=
  THIVdshort maxrc drop 'fTHI := drop
  graphics
  THIVd 1 vp hcursor
  THIVdshort 2 vp hcursor
  text
  "Enter YES to accept the default value, NO to fix it" print input 'accept :=
  if accept 'no = then "Enter the THIVd frame # replacement" print input value 'fTHI :=
endif
  SHAvd f1 takeoff rs 'SHAvdshort :=
  SHAvdshort maxrc drop 'fSHA := drop
  graphics
  SHAvd 1 vp hcursor
  SHAvdshort 2 vp hcursor
  text
  "Enter YES to accept the default value, NO to fix it" print input 'accept :=
  if accept 'no = then "Enter the SHAvd frame # replacement" print input value 'fSHA
:= endif
  FETvd f1 takeoff rs 'FETvdshort :=
  FETvdshort maxrc drop 'fFET := drop
  graphics
  FETvd 1 vp hcursor
  FETvdshort 2 vp hcursor
  text

```

```

"Enter YES to accept the default value, NO to fix it" print input 'accept :=
if accept 'no = then "Enter the FETvd frame # replacement" print input value 'fFET
:= endif

```

```

'HATvdshort discard 'THIvdshort discard 'SHAVdshort discard 'FETvdshort discard

```

```

; Calculating maximum negative impulse of the body.
BCOMz deriv 60 * 'BCOMzvd :=
BCOMzvd bm * 'negI :=
negI f1 COMm rs 'prevnegI :=
prevnegI min 'negIm :=
; "Find the peak negative impulse of bodyCOM." print
; 2 sleep
; graphics
; prevnegI 1 vp hcursor
; text
; "Enter the maximum negative impulse of the body" print input value 'negIm :=
'prevnegI discard
empty

; Calculating peak hip, knee, and ankle angular accelerations during
; the negative phase.
"Finding the peak angular accelerations before flow." print
1 sleep
rHip_aAcc f1 COMm rs 'prevHipacc :=
prevHipacc max 'rHipAccP :=
rKnee_aAcc f1 COMm rs 'prevKneacc :=
prevKneacc max 'rKneeAccP :=
; graphics
; rHip_aAcc 1 vp hcursor
; text
; "Enter peak hip acceleration" print input value 'rHipAccP :=
; graphics
; rKnee_aAcc 1 vp hcursor
; text
; "Enter peak knee acceleration" print input value 'rKneeAccP :=
rAnkle_aAcc f1 COMm rs 'prevAnkacc :=
prevAnkacc max 'rAnkleAccP :=
graphics
prevAnkacc 1 vp hcursor
text
"Enter YES to accept the default value, NO to fix it" print input 'accept :=
if accept 'no = then "Enter peak ankle acceleration" print input value 'rAnkleAccP :=
endif
'prevHipacc discard 'prevKneacc discard 'prevAnkacc discard

```

```

empty

;   Calculating VJP (performance criterion)
BCOMzmax BCOMst - 'Jumpht :=
end

'Save_Files define
BCOMx 1 * 't1 :=
BCOMz 1 * 't2 :=
rHip_Angle 1 * 't3 :=
rKnee_Angle 1 * 't4 :=
rAnkle_Angle 1 * 't5 :=
rHip_aVel 1 * 't16 :=
rKnee_aVel 1 * 't17 :=
rAnkle_aVel 1 * 't18 :=
rHip_aAcc 1 * 't19 :=
rKnee_aAcc 1 * 't20 :=
rAnkle_aAcc 1 * 't21 :=
FIZV 1 * 't6 :=
TOvel 1 * 't7 :=
Mh 1 * 't8 :=
Mk 1 * 't9 :=
Ma 1 * 't10 :=
HATvd 1 * 't12 :=
THIvd 1 * 't13 :=
SHAvd 1 * 't14 :=
FETvd 1 * 't15 :=
hpwr 1 * 't22 :=
kpwr 1 * 't23 :=
apwr 1 * 't24 :=
COPx 1 * 't11 :=
'BCOMx discard 'BCOMz discard 'Hip_Angle discard 'Knee_Angle discard
'Ankle_Angle discard 'FIZV discard 'Mh discard
'Mk discard 'Ma discard 'HATvd discard 'SHAvd discard
'FETvd discard 'COPx discard
'hpwr discard 'kpwr discard 'apwr discard
'rHip_aVel discard 'rKnee_aVel discard 'rAnkle_aVel discard
'rAnkle_aAcc discard 'rHip_aAcc discard 'Knee_aAcc discard
'Ankle_aAcc discard 'Hip_aAcc discard 'rKnee_aAcc discard

[ t1 t2 t3 t4 t5 t16 t17 t18 t19 t20 t21 t6 t7 t8 t9 t10 t12 t13 t14 t15 t22 t23 t24 t11 ]
'list1 :=
'list1 'tmp :=
ttt specialk '.11a + '%10.3f tmp csave

```

't1 discard 't2 discard 't3 discard 't4 discard 't5 discard  
't6 discard 't7 discard 't8 discard 't9 discard 't10 discard  
't11 discard 't12 discard 't13 discard 't14 discard 't15 discard  
't16 discard 't17 discard 't18 discard 't19 discard

trial1 1 \* 't1a :=  
BCOMst 1 \* 't1b :=  
BCOMlow 1 \* 't1c :=  
BCOMto 1 \* 't1d :=  
BCOMpeak 1 \* 't1 :=  
BCOMnet 1 \* 't2 :=  
takeoff 1 \* 't2a :=  
tlow 60 \* 't2b :=  
rHip\_A\_to 1 \* 't3 :=  
rKnee\_A\_to 1 \* 't4 :=  
rAnkle\_A\_to 1 \* 't5 :=  
TV 1 \* 't6 :=  
tprop 1 \* 't7 :=  
AVA 1 \* 't8 :=  
AMP 1 \* 't9 :=  
A\_MechP 1 \* 't10 :=  
TBP3max 1 \* 't11 :=  
mMh 1 \* 't12 :=  
mMk 1 \* 't13 :=  
mMa 1 \* 't14 :=  
Hipjvt 1 \* 't15 :=  
Kneejvt 1 \* 't16 :=  
Anklejvt 1 \* 't17 :=  
Mhjvt 1 \* 't18 :=  
Mkjvt 1 \* 't19 :=  
Majvt 1 \* 't20 :=  
Mht 1 \* 't21 :=  
Mkt 1 \* 't22 :=  
Mat 1 \* 't23 :=  
fHAT 1 \* 't24 :=  
fTHI 1 \* 't25 :=  
fSHA 1 \* 't26 :=  
fFET 1 \* 't27 :=  
negIm 1 \* 't28 :=  
rHipAccP 1 \* 't29 :=  
rKneeAccP 1 \* 't30 :=  
rAnkleAccP 1 \* 't31 :=  
Jumpht 1 \* 't32 :=  
bh 1 \* 't33 :=  
bm 1 \* 't34 :=

```

mMtdiff 1 * 't35 :=
hpwrmax 1 * 't36 :=
kpwrmax 1 * 't37 :=
apwrmax 1 * 't38 :=
hpwrmax# 1 * 't39 :=
kpwrmax# 1 * 't40 :=
apwrmax# 1 * 't41 :=

'BCOMpeak discard 'BCOMnet discard 'Hip_A_to discard 'Knee_A_to discard
'Ankle_A_to discard 'TV discard 'tprop discard 'AMP discard 'AVA discard
'A_MechP discard 'mMh discard 'mMk discard 'mMa discard
'Hipjvt discard 'Kneejvt discard 'Anklejvt discard 'Mhjvt discard
'Mkjvt discard 'Majvt discard 'Mht discard 'Mkt discard 'Mat discard
'fHAT discard 'fTHI discard 'fSHA discard 'fFET discard 'BCOMzmax discard
'negIm discard 'HipAccP discard 'KneeAccP discard 'AnkleAccP discard
'TBPmax discard 'mMtdiff discard
empty

[ t1a t1b t1c t1d t1 t2 t2a t2b t3 t4 t5 t6 t7 t8 t9 t10 t11 t12 t13 t14 t15 t16 t17
t18 t19 t20 t21 t22 t23 t24 t25 t26 t27 t28 t29 t30 t31 t32 t33 t34 t35 t36 t37 t38 t39 t40
t41 ] 'list2 :=
'list2 'alist :=
ttt specialk '.12a + '%11.3f alist csave

't1a discard 't1b discard 't1c discard 't1d discard 't2a discard 't2b discard
't1 discard 't2 discard 't3 discard 't4 discard 't5 discard
't6 discard 't7 discard 't8 discard 't9 discard 't11 discard
't12 discard 't13 discard 't14 discard 't15 discard 't16 discard
't17 discard 't18 discard 't19 discard 't20 discard 't21 discard
't22 discard 't23 discard 't24 discard 't25 discard 't26 discard
't27 discard 't28 discard 't29 discard 't30 discard 't31 discard
't32 discard 't33 discard 't34 discard 't35 discard 't36 discard
't37 discard 't38 discard 't39 discard 't40 discard 't41 discard

zCOMvel 1 * 't1 :=
TBP3 1 * 't2 :=

'TBP discard 'TBP3 discard 'zCOMvel discard

[ t1 t2 ] 'list3 :=
'list3 'hola :=
ttt specialk '.13a + '%11.3f hola csave
't1 discard 't2 discard
"Files are saved" print
; This is the additional cleanup I am doing to save memory.

```

'current discard 'VCOM1x discard 'one discard 'VCOM1z discard  
'VCOM1zr discard 'VCOM2zr discard 'list1 discard  
'list2 discard 'list3 discard 'alist discard  
'VCM1x discard 'VCM1z discard 'VCOM2x discard 'VCOM3zr discard  
'tmp discard 'rKnee\_A\_to discard  
'hola discard 'VCOM4zr discard  
'RT\_Anklezv discard 'VCOM2z discard 'VCOM3x discard  
'VCOM3z discard 'THIvd discard  
'rHip\_Angle discard 'rKnee\_Angle discard 'rAnkle\_Angle discard  
'F1Z discard 'M1Z discard 'F1ZmV discard 'V4TO6znr discard  
'TOvel discard 'F1Zm discard 'V3TO4znr discard 'V2TO3znr discard  
'BCOMzvd discard 'negI discard

empty

end

## APPENDIX E

## Permission of the Human Subjects Committee and Informed Consent Forms

Permission was obtained from the Human Subjects Review Board of the School of Education, The University of Michigan. This appendix includes the letter of approval for the project, as well as copies of the informed consent forms.



THE UNIVERSITY OF MICHIGAN  
SCHOOL OF EDUCATION

OFFICE OF THE DEAN  
400 E. UNIVERSITY, 1105 SEB  
ANN ARBOR, MICHIGAN 48106-1259  
313-764-4470 FAX: 313-763-1129

November 9, 1993

Dr. Homer A. Neal  
Vice President for Research  
4080 Fleming Administration Building - 1340

Dear Vice President Neal:

The School of Education's Human Subjects Review Board has considered (by means of expedited review) and approved as originally proposed the following application for the use of human subjects.

Title: Multivariate Analysis of Kinesiological Factors in Vertical Jump Performance

Researcher's Name and Address: Mr. Luis F. Aragón-Vargas  
2545 Stone Drive  
Ann Arbor, MI 48105

Date Approved: September 21, 1993

This approval is granted with the following provisions:

(1) that the investigator is required to advise the School of Education's Human Subjects Review Board before making any change in protocol which might bring into question the involvement of human subjects in a manner at variance with the consideration on which this approval was based;

(2) that the investigator is required to immediately suspend an inquiry if an unanticipated negative change in the health or behavior of a subject is noticed that may be attributable to the research, and the circumstance shall be promptly reported by the investigator to the School of Education's Human Subjects Review Board for its further review and decision on continuation/termination of the project; and

(3) that every 12 months from the date of approval, a review by the Human Subjects Review Board is required. If a continuing proposal is not submitted for annual review, or if it is not approved as a result of such review, the project will be discontinued, pending later approval.

Sincerely,

David A. Daly, Associate Professor  
Chair, Human Subjects Review Board

/mm  
cc: Mr. Aragón-Vargas, Professor Gross

NOTE TO INVESTIGATOR: Please read carefully items (1) through (3) above, especially noting that approval is valid for only twelve months and an extension must be requested by you before the expiration.

Luis F. Aragón V, M.S.  
Biomechanics Laboratory, 1210 CCRB  
Dept of Movement Science  
The University of Michigan

VERTICAL JUMP PERFORMANCE STUDY  
INFORMED CONSENT FORM

I, \_\_\_\_\_, declare that Luis F. Aragón-Vargas has fully explained to me the procedures and conditions for the research project he is conducting for his Dissertation. The study attempts to understand the limiting factors in vertical jump performance, in order to improve the training techniques used for maximizing this type of performance, and to better understand the way humans execute a multi-articular skill.

My participation in this study is voluntary. I understand that I will be asked to perform fifty maximal vertical jumps, with feet comfortably apart at shoulder width, and hands placed on top of my hips. I will attempt to jump as high as possible without moving my arms. This type of jumps has been previously used in the study of vertical jumping. One minute of rest will be allowed between trials.

The jumps will be performed on a force plate (a rigid metal block embedded in the floor which feels like the floor, but has sensors to measure the forces produced), while movement data are collected by four video cameras. During the experiment, I will be required to wear a swimsuit or shorts, in order to have reflective markers attached to my body at the shoulder, hip, knee, ankle, and tip of the foot.

I understand that, as with any other physical activity, these tests involve some risk of injury, such as ankle sprains if I land incorrectly or muscular strains as a result of a maximal effort. I will follow warm-up and execution instructions carefully to minimize this risk. The investigator has also explained to me that it is possible that I will experience leg muscle soreness for two to three days, starting the day after the experiment. The soreness will go away after the third day, and will not affect my daily activities.

(Informed consent form, vertical jump performance pilot study, page2 of 2)

I understand that the University will provide first aid medical treatment in the unlikely event of physical injury resulting from research procedures. Additional medical treatment will be provided in accordance with the University's determination of its responsibility to do so. The University does not, however, provide compensation to a person who is injured while participating as a subject in research.

The investigator has assured to me that all the information obtained will be strictly confidential and that my identity will not be revealed. Videos of my jumps may be used for communication purposes, but only after my face is electronically edited. I also understand that I can withdraw my consent and discontinue my participation at any time without penalty or loss of benefits to which I would otherwise be entitled. Upon completion of this test, I am entitled to receive \$20 as a compensation for my time and effort.

I certify that, to the best of my knowledge, I have no injuries that would affect my participation in this experiment. I also certify that the rules of the Athletic Department of the University of Michigan do not disqualify me from receiving compensation for my participation in this study or, in that case, I forfeit my right to be compensated. All my questions and concerns have been addressed satisfactorily, and I may obtain more information about the outcome of this study from Luis Aragón at the address listed above.

\_\_\_\_\_  
Signature of participant

\_\_\_\_\_  
Researcher

Social Security #:

Date:

Address:

Telephone Number:

Luis F. Aragón V, M.S.  
Biomechanics Laboratory, 1210 CCRB  
Dept of Movement Science  
The University of Michigan

VERTICAL JUMP PERFORMANCE STUDY  
INFORMED CONSENT FORM

I, \_\_\_\_\_, declare that Luis F. Aragón-Vargas has fully explained to me the procedures and conditions for the research project he is conducting for his Dissertation. The study attempts to understand the limiting factors in vertical jump performance, in order to improve the training techniques used for maximizing this type of performance, and to better understand the way humans execute a multiarticular skill.

My participation in this study is voluntary. I understand that I will be asked to perform five maximal vertical jumps, with feet comfortably apart at shoulder width, and hands placed on top of my hips. I will attempt to jump as high as possible without moving my arms. This type of jumps has been previously used in the study of vertical jumping. One minute of rest will be allowed between trials.

The jumps will be performed on a force plate (a rigid metal block embedded in the floor which feels like the floor, but has sensors to measure the forces produced), while movement data are collected by four video cameras. During the experiment, I will be required to wear a swimsuit or shorts and be barefooted, in order to have reflective markers attached to my body at the shoulder, hip, knee, ankle, and tip of the foot.

I understand that, as with any other physical activity, these tests involve some risk of injury, such as ankle sprains if I land incorrectly or muscular strains as a result of a maximal effort. I will follow warm-up and execution instructions carefully to minimize this risk. The investigator has also explained to me that it is possible that I will experience leg muscle soreness for two to three days, starting the day after the experiment. The soreness will go away after the third day, and will not affect my daily activities.

(Informed consent form, vertical jump performance pilot study, page 2 of 2)

I understand that the University will provide first aid medical treatment in the unlikely event of physical injury resulting from research procedures. Additional medical treatment will be provided in accordance with the University's determination of its responsibility to do so. The University does not, however, provide compensation to a person who is injured while participating as a subject in research.

The investigator has assured to me that all the information obtained will be strictly confidential and that my identity will not be revealed. Videos of my jumps may be used for communication purposes, but only after my face is electronically edited. I also understand that I can withdraw my consent and discontinue my participation at any time without penalty or loss of benefits to which I would otherwise be entitled. Upon completion of this test and the strength test, I am entitled to receive \$20 as a compensation for my time and effort.

I certify that, to the best of my knowledge, I have no injuries that would affect my participation in this experiment. I also certify that the rules of the Athletic Department of the University of Michigan do not disqualify me from receiving compensation for my participation in this study or, in that case, I forfeit my right to be compensated. All my questions and concerns have been addressed satisfactorily, and I may obtain more information about the outcome of this study from Luis Aragón at the address listed above.

\_\_\_\_\_  
Signature of participant

\_\_\_\_\_  
Researcher

Social Security #:

Date:

Address:

Telephone Number:

Luis F. Aragón V, M.S.  
Biomechanics Laboratory, 1210 CCRB  
Dept of Movement Science  
The University of Michigan

VERTICAL JUMP PERFORMANCE PILOT STUDY  
INFORMED CONSENT FORM

I, \_\_\_\_\_, declare that Luis F. Aragón-Vargas has fully explained to me the procedures and conditions for the research project he is conducting for his Dissertation. The study attempts to understand the limiting factors in vertical jump performance, in order to improve the training techniques used for maximizing this type of performance, and to better understand the way humans execute a multiarticular skill. This particular test deals with measuring strength in a reliable manner, in order to relate it to vertical jump performance.

My participation in this study is voluntary. I understand that I will be asked to perform three maximal isometric (static) contractions for each one of five joint tests: hip extension, hip flexion, knee extension, knee flexion, and ankle plantar flexion. The tests will be carried out on a Biodex isokinetic evaluation and training device, following standard procedures for isometric testing. Warm-up will consist of five minutes of pedalling on a stationary bicycle, followed by three isometric practice trials before each joint test. Then, I will do the three maximal isometric contractions, which I will sustain for five seconds each. I will have 15 seconds to rest between trials. I understand that in order to isolate the muscle groups that will be tested, velcro straps will be used to secure my torso, hips and contralateral limb, but my arms and hands will be free.

I understand that, as with any other physical activity, these tests involve some risk of injury, such as muscular strains as a result of a maximal effort. I will follow warm-up and execution instructions carefully to minimize this risk. The investigator has also explained to me that it is possible that I will experience leg muscle soreness for two to three days, starting the day after the experiment. The soreness will go away after the third day, and will not affect my daily activities.

I understand that the University will provide first aid medical treatment in the unlikely event of physical injury resulting from research procedures. Additional medical treatment will be provided in accordance with the University's determination of its responsibility to do so. The University does not, however, provide compensation to a person who is injured while participating as a subject in research.

(Informed consent form, vertical jump performance pilot study, page 2 of 2)

The investigator has assured to me that all the information obtained will be strictly confidential and that my identity will not be revealed. I also understand that I can withdraw my consent and discontinue my participation at any time without penalty or loss of benefits to which I would otherwise be entitled. Upon completion of this test and the jumping test, I am entitled to receive \$20 as a compensation for my time.

I certify that, to the best of my knowledge, I have no injuries that would affect my participation in this experiment. I also certify that the rules of the Athletic Department of the University of Michigan do not disqualify me from receiving compensation for my participation in this study. All my questions and concerns have been addressed satisfactorily, and I may obtain more information about the outcome of this study from Luis Aragón at the address listed above.

\_\_\_\_\_  
Signature of participant

  
\_\_\_\_\_  
Researcher

Social Security #:

Date: )

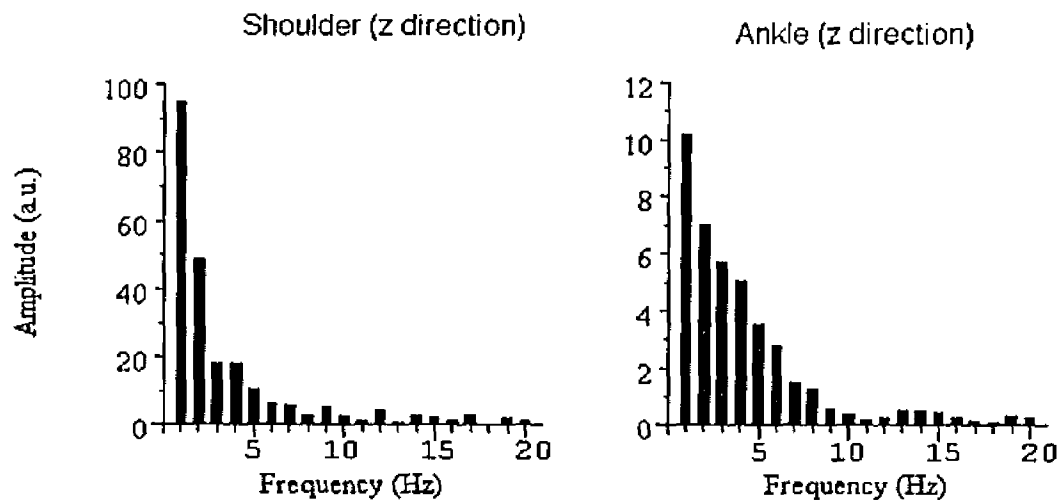
Address:

Telephone Number:

## APPENDIX F

### Choice of Filter Cutoff Frequency

During the process of data acquisition there is normally a certain amount of high-frequency noise. In the process of differentiation this noise is amplified considerably, as a function of frequency. Since human movement is characterized by low frequencies (Winter 1990), it is highly desirable to selectively attenuate the higher frequencies with a low-pass filter. A major decision in the process of filter design is the choice of a cutoff frequency ( $f_c$ ): if  $f_c$  is set very low, noise reduction is very effective, but the signal is considerably distorted; if  $f_c$  is set too high, there is less signal distortion, but too much noise is allowed to pass. The choice of filter cutoff frequency is enhanced by knowledge of the particular signal of concern. Figure F.1 plots the amplitude of joint marker motion, obtained from a Fourier transform of the video position data of one particular subject during a vertical jump, for each frequency from 1 to 20 Hz. Two joint markers are shown, corresponding to two joints (shoulder and ankle) that behave very differently during vertical jumping.



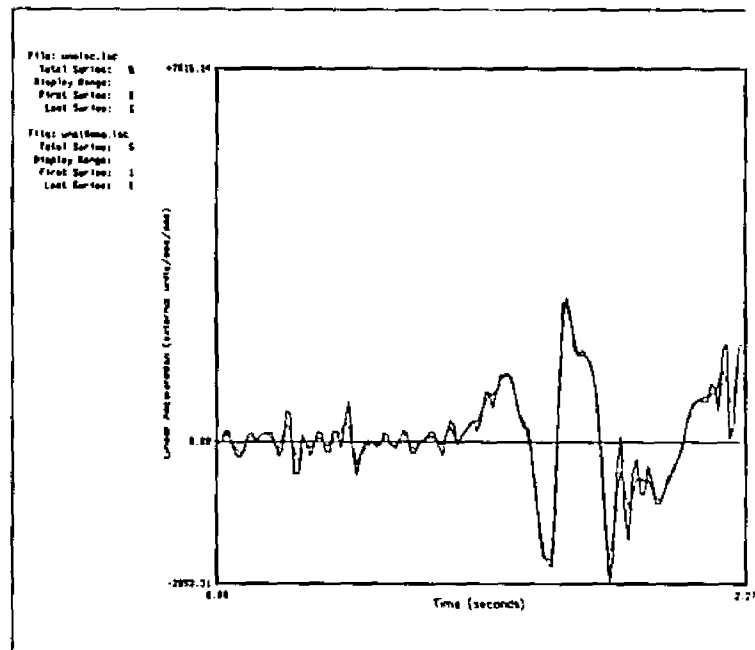
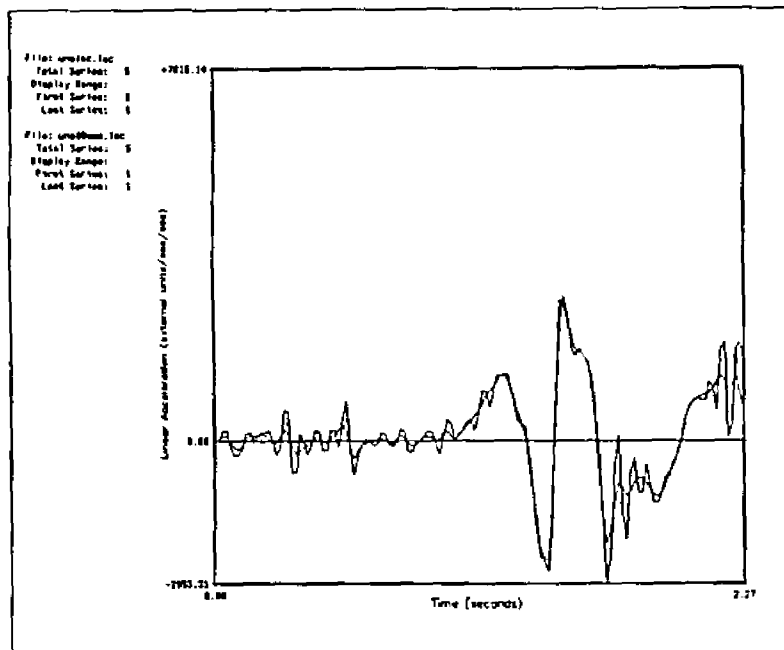
**Figure F.1.** Amplitude of signal from a Fourier transform of video position data, file DB01T01.RAW. Amplitude is reported in arbitrary units (a.u.).

Table F.1 shows the signal power that is present below each of three potential cutoff frequencies: 6, 8, and 10 Hz, for each of the joint markers. Notice that there are no clear differences from joint to joint, except for the knee in the x direction. There seems to be less signal power for movement in the x direction than for movement in the z direction at any particular frequency: about 75% of the signal is present below 8 Hz in the x direction, compared to about 85% of the signal in the z direction.

**Table F.1.** Signal power at 6, 8, and 10 Hz. File DB01101.RAW. Direction "x" corresponds to the anterior-posterior direction, "z" to the superior-inferior direction.

Marker	% of signal below $f_c$ (x direction)			% of signal below $f_c$ (z direction)		
	6 Hz	8 Hz	10 Hz	6 Hz	8 Hz	10 Hz
Shoulder	71.7	76.6	82.0	80.4	83.9	87.3
Hip	78.7	85.0	88.9	81.6	84.5	87.6
Knee	65.7	71.6	77.4	82.8	85.2	87.8
Ankle	75.5	79.1	81.9	81.6	88.0	90.2
Toe	76.7	80.9	84.2	77.7	87.5	90.5

Figure F.2 compares the effect of filtering the position data with  $f_c = 8$  Hz and with  $f_c = 10$  Hz, on shoulder acceleration data. The 10 Hz filter keeps a considerable portion of the noise, compared to the 8 Hz filter. A 6 Hz filter would reduce the noise even further, but it is clear from Table F.1 that signal distortion is increased.  $f_c$  was selected at 8 Hz.



**Figure F.2.** Effects of filtering the position data on shoulder acceleration data. The left graph plots the raw signal superimposed on the filtered signal at  $f_c = 8$  Hz. The right graph plots the raw signal superimposed on the data filtered at  $f_c = 10$  Hz.

## APPENDIX G

### "Best" Prediction Models for Remaining Subjects

In Chapter III of this dissertation, data from eight subjects were analyzed, but only three of them were discussed in detail. This appendix includes the tables with the best prediction models for the remaining five subjects, for comparison purposes. In each table, for each level, the three best multiple-predictor models are presented, together with the best single predictor. Deviations from this standard are due to the fact that sometimes it was not possible to identify three models that were significant, and in some cases not even one multiple-predictor model was significant. Other times, no single predictor would reach significance. Prediction models at level III where the dependent variable was either TOVEL or BCOMNET show the best model and the best single predictor only, using dynamic or kinematic predictors alone. This was done to test hypotheses 12 and 14.

**Table G.1.** "Best" prediction models at each level of analysis, subject D103.

Prediction model for VJP	R <sup>2</sup>	R <sub>a</sub> <sup>2</sup>	p-value
<b>LEVEL I</b>			
1) VJP = k + tovel + trial	.50	.48	< .0001
2) VJP = k + tovel	.12	.10	= .01
<b>LEVEL II</b>			
3) BCOMNET = k + hipangto + kneangto + trial	.90	.89	< .0001
4) BCOMNET = k + hipangto	.65	.64	< .0001
5) TOVEL = k + peakpwr + amechp + tprop - trial	.83	.81	< .0001
6) TOVEL = k + peakpwr + amechp - trial + amp	.80	.78	< .0001
7) TOVEL = k + peakpwr - trial	.73	.72	< .0001
8) TOVEL = k + peakpwr	.50	.49	< .0001
9) TOVEL = k + ava	.27	.25	< .0001
10) VJP = k + amechp + peakpwr + tprop + trial	.78	.76	< .0001
11) VJP = k + amechp + peakpwr - ava + trial - negimmax	.73	.70	< .0001
12) VJP = k + peakpwr - ava + amechp	.68	.66	< .0001
13) VJP = k + peakpwr	.21	.19	= .0009
14) VJP = k + amechp	.17	.15	= .003
<b>LEVEL III</b>			
15) VJP = k + hippwrmax + knemmax + trial	.53	.50	< .0001
16) VJP = k + hippwrmax + knemmax	.44	.42	< .0001
17) VJP = k + hippwrmax + knemrev	.33	.30	< .0001
18) VJP = k + hippwrmax	.18	.17	= .002
19) TOVEL = k + hippwrmax + knemmax + ankmrev - trial	.61	.58	< .0001
20) TOVEL = k + hipmmax	.22	.21	= .0005
21) TOVEL = k + protodis + jrevtdif - mmtdif - trial	.62	.57	< .0001
22) TOVEL = k + hipaccpk	.19	.18	= .001
24) BCOMNET = k + hipmmax + knepwrmax + ankpwrmax - ankmrev + knemmax	.45	.39	< .0001
25) BCOMNET = k + ankpwrmax - ankmrev	.29	.26	= .0003
26) BCOMNET = k + ankpwrmax	.22	.20	= .0005

**Table G.2.** "Best" prediction models at each level of analysis, subject DI04.

<b>Prediction model for VJP</b>	<b>R<sup>2</sup></b>	<b>R<sub>a</sub><sup>2</sup></b>	<b>p-value</b>
<b>LEVEL I</b>			
1) VJP = k + tovel	.32	.31	< .0001
<b>LEVEL II</b>			
2) BCOMNET = k + ankancto + hipangto + kneangto	.91	.91	< .0001
3) BCOMNET = k + ankancto	.84	.84	< .0001
4) TOVEL = k + peakpwr + ava + amp - trial	.73	.70	< .0001
5) TOVEL = k + peakpwr - trial	.67	.65	< .0001
6) TOVEL = k + peakpwr + amp	.64	.62	< .0001
7) TOVEL = k + peakpwr	.59	.58	< .0001
8) TOVEL = k + ava	.26	.25	= .0002
9) VJP = k + peakpwr <sup>a</sup>	.25	.24	= .0003
10) VJP = k + ava	.15	.13	= .007
<b>LEVEL III</b>			
11) VJP = k + ankmmx - kneaccpk - jrevtdif <sup>b</sup>	.23	.18	= .008
12) TOVEL = k + hipmrev - trial	.30	.27	= .0004
13) TOVEL = k + ankmmx - trial	.24	.21	= .002
14) TOVEL = k - jrevtdif - trial	.16	.12	= .019
15) BCOMNET = k + ankpwrmax - trial	.35	.32	< .0001
16) BCOMNET = k + ankpwrmax - hipmrev	.32	.29	= .0002
17) BCOMNET = k + ankpwrmax	.19	.17	= .002

a) No significant models with more than one variable were identified.

b) No significant single-predictor models were identified.

**Table G.3.** "Best" prediction models at each level of analysis, subject DI05. This subject performed "squat jumps", with very little counter-movement.

Prediction model for VJP	R <sup>2</sup>	R <sub>a</sub> <sup>2</sup>	p-value
<b>LEVEL I</b>			
1) VJP = k + tovel	.26	.24	= .0002
<b>LEVEL II</b>			
2) BCOMNET = k + ankancto + kneangto + hipangto	.87	.86	< .0001
3) BCOMNET = k + ankancto	.80	.79	< .0001
4) TOVEL = k + ava + amp - trial	.86	.85	< .0001
5) TOVEL = k + ava - trial - negimmax	.82	.81	< .0001
6) TOVEL = k + ava + amp	.80	.79	< .0001
7) TOVEL = k + ava	.77	.76	< .0001
8) TOVEL = k - negimmax	.50	.49	< .0001
9) VJP = k + ava + amp	.31	.28	= .0002
10) VJP = k + amp - tprop - trial	.30	.25	= .001
11) VJP = k + ava	.19	.17	= .002
12) VJP = k - negimmax	.11	.09	= .019
<b>LEVEL III</b>			
13) VJP = k + hipmmax - trial	.33	.30	= .0001
14) VJP = k + ankmmax	.32	.31	< .0001
15) VJP = k + ankmrev	.26	.24	= .0002
16) TOVEL = k - knemmax - trial	.58	.56	< .0001
17) TOVEL = k + hipmmax - trial	.51	.49	< .0001
19) TOVEL = k - knemmax	.29	.28	< .0001
20) BCOMNET = k - mmtdiff	.13	.11	= .012

**Table G.4.** "Best" prediction models at each level of analysis, subject DI06.

<b>Prediction model for VJP</b>	<b>R<sup>2</sup></b>	<b>R<sub>a</sub><sup>2</sup></b>	<b>p-value</b>
<b>LEVEL I</b>			
1) VJP = k + tovel + bcomnet	.49	.47	< .0001
2) VJP = k + tovel	.41	.39	< .0001
<b>LEVEL II</b>			
3) BCOMNET = k + ankancto + hipangto	.89	.89	< .0001
4) BCOMNET = k + ankancto	.86	.86	< .0001
5) TOVEL = k + peakpwr + amechp + tprop - trial	.68	.65	< .0001
6) TOVEL = k + peakpwr + amechp + tprop	.61	.59	< .0001
7) TOVEL = k + peakpwr + amechp + amp	.51	.48	< .0001
8) TOVEL = k + amechp	.23	.21	= .0005
9) TOVEL = k + peakpwr	.21	.19	= .0009
10) VJP = k + amechp + peakpwr + amp + tprop - trial	.65	.61	< .0001
11) VJP = k + tprop + amp + amechp - trial	.61	.57	< .0001
12) VJP = k + amp + amechp - trial	.57	.54	< .0001
13) VJP = k + amechp	.24	.22	= .0004
<b>LEVEL III</b>			
14) VJP = k + hipacepk - jrevtdif	.27	.24	= .0007
15) VJP = k - jrevtdif	.17	.15	= .003
16) VJP = k + hipacepk	.14	.12	= .009
17) TOVEL = k + hippwrmax + hipmrev	.35	.32	< .0001
18) TOVEL = k + hippwrmax	.28	.27	< .0001
19) TOVEL = k + hipmrev	.22	.20	= .0007
20) TOVEL = k + hipacepk	.12	.10	= .017
21) BCOMNET = k + ankpwrmax - ankmmax	.34	.31	< .0001
22) BCOMNET = k + ankpwrmax	.28	.26	= .0001
23) BCOMNET = k - protodis	.01	.00	= .48

**Table G.5.** "Best" prediction models at each level of analysis, subject DI08.

<b>Prediction model for VJP</b>	<b>R<sup>2</sup></b>	<b>R<sub>a</sub><sup>2</sup></b>	<b>p-value</b>
<b>LEVEL I</b>			
1) VJP = k + tovel + trial	.53	.51	< .0001
2) VJP = k + tovel + bcomnet	.26	.23	= .001
3) VJP = k + tovel	.16	.14	= .005
<b>LEVEL II</b>			
4) BCOMNET = k + ankancto + kneangto + trial	.91	.91	< .0001
5) BCOMNET = k + kneangto	.83	.82	< .0001
6) TOVEL = k + peakpwr + amechp + tprop	.73	.71	< .0001
7) TOVEL = k + peakpwr + tprop - negimmax	.56	.53	< .0001
8) TOVEL = k + peakpwr + amechp - ava	.53	.50	< .0001
9) TOVEL = k + peakpwr	.22	.21	= .0007
10) VJP = k + amechp + peakpwr -ava + amp	.79	.77	< .0001
11) VJP = k + amechp + peakpwr + amp + tprop	.77	.75	< .0001
12) VJP = k + peakpwr - ava + amechp	.77	.75	< .0001
13) VJP = k - negimmax	.42	.40	< .0001
<b>LEVEL III</b>			
14) VJP = k + hipmmax - ankpwrmax + trial	.64	.61	< .0001
15) VJP = k + hipmmax - ankmmmax	.60	.59	< .0001
16) VJP = k + hipmmax - ankpwrmax + knepwrmax	.60	.57	< .0001
17) VJP = k + hipmmax	.45	.44	< .0001
18) TOVEL = k + hipmmax - ankmmmax - trial	.26	.21	= .004
19) TOVEL = k + hipmmax	.09	.07	= .035
20) TOVEL = k + hipacepk	.01	.00	= .50
21) BCOMNET = k + knepwrmax + ankmmmax - knemmax	.17	.11	= .04
22) BCOMNET = k - knemmax + trial	.15	.11	= .029
23) BCOMNET = k + hipacepk	.08	.06	= .05

## APPENDIX H

### Single Correlation Matrices

Both Chapters II and III present tables summarizing the "best" multivariate models for predicting VJP, TOVEL, and BCOMNET, together with the best single predictors for each case. This appendix includes the correlation matrices for the between-subject differences study and each one of the subjects in the within-subject study. As a general guideline for a sample size of 50, correlation coefficients greater than 0.27 are statistically significant.

Table H.1 Pearson correlation matrix for the between-subject differences data, n = 10. Variables not included were constant.

	VJP	TOVEL	BCOMNET	BCOMLG10	HIPANGTO	KNEANGTO	ANKANGTO	TPROP	AVA	AMP	AMECHP	PEAKPWR	NEGIMMAX	HIPMMAX	KNEMMAX	ANKMMAX
VJP	1															
TOVEL	0.962	1														
BCOMNET	0.371	0.247	1													
BCOMLG10	0.367	0.235	0.993	1												
HIPANGTO	0.147	0.124	0.293	0.293	1											
KNEANGTO	-0.022	-0.06	0.444	0.44	0.437	1										
ANKANGTO	0.201	0.184	0.441	0.433	0.028	0.501	1									
TPROP	-0.228	-0.278	-0.054	-0.071	-0.137	-0.054	-0.126	1								
AVA	0.491	0.558	0.069	0.076	0.186	0.059	0.174	-0.91	1							
AMP	0.345	0.268	0.377	0.368	-0.061	0.076	0.066	0.677	-0.515	1						
A_MECHP	0.659	0.659	0.267	0.251	0.21	0.077	0.124	-0.604	0.718	-0.126	1					
PEAKPWR	0.681	0.718	0.238	0.201	0.244	0.059	0.134	-0.332	0.527	-0.026	0.881	1				
NEGIMMAX	-0.314	-0.261	-0.197	-0.213	0.05	-0.003	0.081	0.201	-0.209	-0.22	-0.492	-0.259	1			
HIPMMAX	0.524	0.533	0.237	0.226	-0.019	-0.062	-0.006	-0.165	0.254	0.239	0.691	0.639	-0.702	1		
KNEMMAX	0.23	0.16	0.195	0.188	0.126	0.09	-0.148	-0.019	0.106	0.18	0.445	0.341	-0.452	0.359	1	
ANKMMAX	0.397	0.4	0.123	0.091	0.239	-0.037	-0.065	-0.511	0.59	-0.289	0.802	0.728	-0.346	0.539	0.405	1
HIPMREV	0.483	0.475	0.187	0.192	-0.097	-0.07	0.018	-0.255	0.305	0.21	0.668	0.508	-0.845	0.934	0.348	0.482
KNEMREV	0.173	0.114	0.137	0.129	0.105	0.092	-0.12	-0.059	0.125	0.154	0.403	0.241	-0.508	0.308	0.958	0.371
ANKMREV	0.404	0.399	0.165	0.14	0.268	-0.024	-0.016	-0.469	0.54	-0.216	0.807	0.709	-0.36	0.606	0.447	0.843
HIPACCPK	0.457	0.455	0.241	0.26	0.043	0.094	0.054	-0.55	0.585	-0.008	0.56	0.304	-0.676	0.531	0.306	0.306
KNEACCPK	0.261	0.238	0.128	0.128	0.017	0.103	0.053	-0.439	0.512	-0.131	0.44	0.221	-0.395	0.179	0.619	0.445
ANKACCPK	0.061	0.072	-0.092	-0.066	0.236	0.055	0.03	-0.275	0.249	-0.22	0.194	0.128	-0.084	-0.006	0.097	0.256
HEIGHT	0.101	0.034	0.246	0.239	0.053	-0.045	-0.047	-0.044	0.022	-0.125	0.323	0.347	-0.253	0.294	0.288	0.322
WEIGHT	0.052	0.036	0.132	0.094	0.146	0.047	-0.061	0.006	-0.034	-0.035	0.565	0.64	-0.241	0.538	0.447	0.539
MMTOIFF	-0.095	-0.152	-0.012	-0.011	-0.028	-0.008	-0.087	0.654	-0.556	0.463	-0.298	-0.093	0.092	-0.126	0.019	-0.434
HIPWRMAX	0.665	0.658	0.369	0.35	0.025	0.023	0.141	-0.118	0.254	0.309	0.569	0.611	-0.474	0.821	0.108	0.373
KNEWRMAX	0.505	0.485	0.22	0.211	0.163	-0.067	0.021	-0.243	0.403	-0.023	0.637	0.643	-0.349	0.482	0.627	0.512
ANKWRMAX	0.291	0.252	0.23	0.199	0.34	0.268	0.101	-0.274	0.404	-0.141	0.599	0.641	-0.118	0.254	0.507	0.569
HIPEXTIS	0.212	0.199	0.164	0.149	0.143	0.02	-0.049	0.014	0.018	0.137	0.378	0.401	-0.272	0.421	0.243	0.218
HIPFLXIS	0.337	0.34	0.2	0.167	-0.006	-0.124	-0.015	-0.213	0.262	0.031	0.64	0.613	-0.351	0.52	0.339	0.519
KNEEXTIS	0.467	0.426	0.267	0.235	0.099	-0.058	0.049	-0.192	0.263	0.032	0.731	0.746	-0.4	0.623	0.332	0.584
KNEFLXIS	0.308	0.294	0.147	0.118	0.066	-0.042	-0.045	-0.14	0.151	-0.06	0.599	0.681	-0.269	0.539	0.251	0.494
ANKPFXIS	0.306	0.249	0.522	0.495	-0.021	-0.057	0.366	-0.151	0.145	0.069	0.346	0.378	-0.051	0.203	0.03	0.152
PROTODIS	0.047	0.044	0.042	0.041	-0.006	0.033	0.035	-0.08	0.089	-0.038	0.213	0.212	-0.133	0.103	0.287	-0.008
DISTOPRO	-0.032	-0.035	-0.118	-0.118	-0.11	-0.158	-0.112	0.207	-0.164	0.065	-0.207	-0.077	0.104	-0.212	-0.114	-0.069
OTHEPLR	-0.037	-0.034	-0.009	-0.008	0.036	0.011	-0.004	0.023	-0.044	0.02	-0.155	-0.19	0.103	-0.044	-0.254	0.027
PRODISTA	-0.055	-0.093	0.048	0.048	0.347	0.271	0.266	0.043	-0.028	-0.028	-0.045	-0.019	0.026	-0.03	-0.246	-0.038
OTHEPRD	0.055	0.093	-0.048	-0.046	-0.347	-0.271	-0.266	-0.043	0.028	0.028	0.045	0.019	-0.026	0.03	0.246	0.038
JREVTDF	-0.1	-0.101	0.067	0.057	0.002	0.016	0.071	0.417	-0.354	0.116	-0.256	0.031	0.523	-0.168	-0.092	-0.113
HATL	-0.036	-0.09	0.108	0.103	-0.123	-0.066	0.093	0.099	-0.104	0.013	0.169	0.144	-0.251	0.218	0.269	0.243
THL	-0.125	-0.096	0.039	0.039	0.203	0.139	-0.175	-0.059	-0.01	-0.106	-0.023	-0.024	-0.138	0.004	0.056	-0.064
SHAL	0.208	0.127	0.191	0.196	0.159	-0.073	-0.045	-0.151	0.156	-0.107	0.415	0.391	-0.158	0.251	0.262	0.468
FETL	-0.139	-0.185	0.267	0.259	0.039	0.036	-0.095	0.214	-0.261	0.097	-0.054	0.035	-0.151	0.147	0.106	0.032
HORVELAB	0.032	-0.005	-0.044	-0.05	-0.345	-0.18	-0.324	0.135	-0.115	0.264	0.014	-0.096	-0.35	0.167	0.49	0.025

	HIPMREV	KNEMREV	ANKMREV	HIPACCPK	KNEACCPK	ANKACCPK	HEIGHT	WEIGHT	MMTDIFF	HIPPWRMAX	KNEPWRMAX	ANKPWRMAX	HIPEXTIS	HIPFLXIS	KNEEXT
VJP															
TOVEL															
BCOMNET															
BCOMLG10															
HIPANGTO															
KNEANGTO															
ANKANGTO															
TPROP															
AVA															
AMP															
A_MECHP															
PEAKPWR															
NEGIMMAX															
HIPMMAX															
KNEMMAX															
ANKMMAX															
HIPMREV	1														
KNEMREV	0.357	1													
ANKMREV	0.513	0.388	1												
HIPACCPK	0.665	0.377	0.292	1											
KNEACCPK	0.295	0.67	0.361	0.464	1										
ANKACCPK	0.081	0.137	0.219	0.164	0.281	1									
HEIGHT	0.26	0.218	0.355	0.027	0.043	0.023	1								
WEIGHT	0.404	0.363	0.593	-0.002	0.01	0.092	0.464	1							
MMTDIFF	-0.14	-0.058	-0.38	-0.313	-0.387	-0.258	0.042	0.096	1						
HIPPWRMAX	0.735	0.045	0.415	0.416	0.004	-0.042	0.261	0.292	-0.05	1					
KNEPWRMAX	0.4	0.44	0.605	0.272	0.276	0.119	0.415	0.393	-0.074	0.44	1				
ANKPWRMAX	0.171	0.445	0.525	0.189	0.342	0.092	0.265	0.496	0.125	0.179	0.475	1			
HIPEXTIS	0.354	0.175	0.232	0.068	-0.184	-0.266	0.212	0.469	0.189	0.361	0.322	0.257	1		
HIPFLXIS	0.48	0.298	0.492	0.251	0.231	0.183	0.366	0.621	-0.013	0.376	0.457	0.396	0.417	1	
KNEEXTIS	0.556	0.249	0.602	0.216	0.095	-0.037	0.508	0.68	0.033	0.523	0.559	0.428	0.597	0.62	1
KNEFLXIS	0.45	0.17	0.487	0.122	-0.083	-0.007	0.552	0.699	0.021	0.505	0.547	0.455	0.58	0.533	0.791
ANKPFXIS	0.133	-0.006	0.236	0.091	-0.103	-0.164	0.202	0.33	-0.063	0.238	0.268	0.183	0.374	0.366	0.505
PROTODIS	0.084	0.276	0.139	0.153	0.08	-0.057	0.339	0.237	0.206	0.079	0.234	0.46	0.23	0.259	0.264
DISTOPRO	-0.163	-0.085	-0.343	-0.18	-0.142	-0.048	-0.004	-0.154	0.243	-0.098	-0.133	0.073	-0.096	-0.088	-0.204
OTHERJR	-0.039	-0.251	-0.044	-0.103	-0.04	0.07	-0.337	-0.194	-0.272	-0.052	-0.196	-0.479	-0.203	-0.234	-0.207
PRODISTA	-0.01	-0.211	-0.023	-0.025	-0.297	0.098	0.097	-0.02	0.147	0.086	0.083	0.115	-0.062	-0.115	0.05
OTHERVD	0.01	0.211	0.023	0.025	0.297	-0.098	-0.097	0.02	-0.147	-0.086	-0.083	-0.115	0.062	0.115	-0.05
JREVTDIF	-0.366	-0.243	-0.189	-0.554	-0.263	-0.206	0.042	0.141	0.283	-0.1	-0.063	0.044	0.013	-0.03	-0.002
HATL	0.222	0.262	0.353	-0.066	0.16	0.288	0.604	0.41	0.046	0.095	0.191	0.25	-0.044	0.315	0.225
THIL	0.005	0.042	-0.123	0.076	-0.179	-0.37	0.263	0.003	0.002	-0.033	0.069	-0.067	0.388	-0.089	0.14
SHAL	0.234	0.214	0.501	0.056	0.142	0.309	0.751	0.407	-0.062	0.258	0.424	0.341	-0.005	0.368	0.478
FETL	0.053	0.034	0.06	-0.103	-0.285	-0.381	0.49	0.225	0.188	0.089	0.196	0.135	0.26	-0.02	0.151
HORVELAB	0.206	0.503	-0.004	0.21	0.295	-0.098	0.008	-0.009	0.042	0.07	0.148	-0.041	0.079	0.124	0.017

KNEFLXIS ANKPFIXIS PROTODIS DISTOPRO OTHERJR PRODISTA OTHERVD JREVTDF HATL THIL SHAL FETL HORVELAB

VJP  
 TOVEL  
 BCOMNET  
 BOOMLG10  
 HIPANGTO  
 KNEANGTO  
 ANKANGTO  
 TPROP  
 AVA  
 AMP  
 A\_MECHP  
 PEAKPWR  
 NEGIMMAX  
 HIPMMAX  
 KNEMMAX  
 ANKMMAX  
 HIPMREV  
 KNEMREV  
 ANKMREV  
 HIPACCPK  
 KNEACCPK  
 ANKACCPK  
 HBGHT  
 WEIGHT  
 MMTDIFF  
 HIPPWMAX  
 KNEPWMAX  
 ANKPWMAX  
 HIPEXTIS  
 HIPFLXIS  
 KNEEXTIS  
 KNEFLXIS  
 ANKPFIXIS  
 PROTODIS  
 DISTOPRO  
 OTHERJR  
 PRODISTA  
 OTHERVD  
 JREVTDF  
 HATL  
 THIL  
 SHAL  
 FETL  
 HORVELAB

KNEFLXIS	1													
ANKPFIXIS	0.401	1												
PROTODIS	0.303	0.12	1											
DISTOPRO	-0.11	-0.07	-0.125	1										
OTHERJR	-0.272	-0.1	-0.062	-0.151	1									
PRODISTA	0.094	-0.011	0.042	0.068	-0.06	1								
OTHERVD	-0.094	0.011	-0.042	-0.068	0.06	-1	1							
JREVTDF	0.004	0.048	-0.116	0.039	0.105	-0.11	0.11	1						
HATL	0.281	0.056	0.352	-0.04	-0.34	0.106	-0.106	-0.032	1					
THIL	0.081	0.043	0.065	0.012	-0.068	0.037	-0.037	-0.088	-0.363	1				
SHAL	0.487	0.129	0.328	-0.095	-0.301	0.154	-0.154	0.009	0.5	-0.057	1			
FETL	0.295	0.189	0.151	-0.004	-0.149	0.111	-0.111	0.188	0.15	0.44	0.209	1		
HORVELAB	-0.066	-0.157	0.178	0.074	-0.198	-0.295	0.295	-0.107	0.027	0.008	0.021	-0.089	1	

**Table H.2 Pearson correlation matrix, subject di10 (average jumper), n = 48. Variables not included were constant.**

	VJP	TOVEL	BCOMNET	TRIAL	HIPANGTO	KNEANGTO	ANKANGTO	TPROP	AVA	AMP	AMECHP
VJP	1										
TOVEL	0.618	1									
BCOMNET	0.411	-0.055	1								
TRIAL	0.27	-0.355	0.371	1							
HIPANGTO	0.24	0.066	0.723	0.044	1						
KNEANGTO	-0.254	-0.184	0.652	-0.041	0.562	1					
ANKANGTO	0.277	-0.078	0.922	0.278	0.607	0.707	1				
TPROP	0.296	0.005	0.393	0.118	0.305	0.156	0.31	1			
AVA	-0.07	0.338	-0.387	-0.241	-0.261	-0.199	-0.318	-0.937	1		
AMP	0.558	0.123	0.827	0.428	0.548	0.404	0.776	0.513	-0.436	1	
A_MECHP	0.281	0.38	-0.209	0.074	-0.23	-0.342	-0.177	-0.771	0.857	-0.055	1
PEAKPWR	0.116	0.603	-0.144	-0.724	0.01	0.127	-0.113	-0.06	0.27	-0.302	-0.006
NEGIMMAX	-0.199	-0.042	0.04	-0.172	-0.023	0.192	-0.01	-0.156	0.137	-0.333	-0.169
HIPMMAX	0.021	0.104	-0.02	0.215	-0.068	0.109	0.019	-0.115	0.154	0.134	0.249
KNEMMAX	0.246	0.274	-0.087	-0.187	0.069	-0.392	-0.062	-0.103	0.174	-0.042	0.211
ANKMMAX	0.216	0.409	-0.075	-0.472	0.014	-0.061	0.018	-0.347	0.468	-0.306	0.288
HIPMREV	-0.012	-0.002	-0.247	0.281	-0.23	-0.175	-0.192	-0.243	0.23	0.05	0.423
KNEMREV	0.068	0.101	-0.149	-0.084	-0.024	-0.349	-0.094	-0.232	0.237	-0.102	0.261
ANKMREV	0.024	0.244	-0.279	-0.374	-0.23	-0.153	-0.203	-0.451	0.51	-0.482	0.303
HIPACCPK	-0.046	0.045	0.06	-0.122	0.232	0.148	0.059	-0.125	0.135	0.137	0.174
KNEACCPK	0.141	-0.166	0.077	0.505	0.002	-0.206	0.079	-0.184	0.117	0.253	0.382
ANKACCPK	0.322	0.269	0.11	0.287	0.143	-0.097	-0.004	-0.049	0.139	0.294	0.33
MMTDIFF	-0.023	0.034	0.003	-0.054	-0.037	0.028	0.043	0.132	-0.114	0.061	-0.109
HIPPWRMAX	-0.022	0.132	0.179	-0.246	0.263	0.493	0.174	0.239	-0.163	0.07	-0.283
KNEPWRMAX	0.275	0.356	-0.026	-0.295	0.148	-0.313	-0.002	-0.076	0.176	0.046	0.224
ANKPWRMAX	-0.387	0.054	-0.083	-0.573	0.038	0.461	-0.005	-0.025	0.053	-0.382	-0.345
PROTODIS	-0.644	-0.403	-0.262	-0.082	-0.265	0.301	-0.196	-0.244	0.101	-0.378	-0.128
OTHERJR	0.644	0.403	0.262	0.082	0.265	-0.301	0.196	0.244	-0.101	0.378	0.128
JREVDIF	0.243	0.371	0.039	-0.555	0.245	-0.085	0.007	0.214	-0.088	-0.129	-0.237
HORVELAB	0.231	0.357	-0.258	0.046	-0.221	-0.303	-0.185	-0.02	0.137	-0.023	0.241

PEAKPWR NEGIMMAX HIPMMAX KNEMMAX ANKMMAX HIPMREV KNEMREV ANKMREV HIPACCPK KNEACCPK ANKACCPK

VJP												
TOVEL												
BCOMNET												
TRIAL												
HIPANGTO												
KNEANGTO												
ANKANGTO												
TPROP												
AVA												
AMP												
A_MECHP												
PEAKPWR	1											
NEGIMMAX	0.313	1										
HIPMMAX	-0.094	-0.254	1									
KNEMMAX	-0.024	-0.046	-0.301	1								
ANKMMAX	0.674	0.187	-0.192	0.229	1							
HIPMREV	-0.28	-0.541	0.747	-0.25	-0.243	1						
KNEMREV	-0.189	-0.082	-0.263	0.873	0.138	-0.183	1					
ANKMREV	0.526	0.255	-0.017	0.258	0.687	-0.135	0.178	1				
HIPACCPK	-0.046	-0.297	0.172	0.249	0.017	0.36	0.161	-0.06	1			
KNEACCPK	-0.616	-0.34	0.195	0.219	-0.255	0.326	0.295	-0.133	0.09	1		
ANKACCPK	-0.114	-0.374	0.208	0.136	-0.183	0.275	0.108	-0.138	0.267	0.259	1	
MMTDIFF	0.102	-0.061	0.046	-0.253	-0.026	0.282	-0.354	-0.141	0.145	-0.284	-0.059	
HIPPWRMAX	0.512	0.037	0.327	-0.575	0.175	0.106	-0.573	-0.019	0.003	-0.343	-0.128	
KNEPWRMAX	0.074	-0.083	-0.127	0.831	0.224	-0.066	0.616	0.21	0.308	-0.003	0.036	
ANKPWRMAX	0.645	0.391	-0.049	-0.171	0.367	-0.291	-0.176	0.313	0.053	-0.489	-0.389	
PROTODIS	-0.023	0.231	0.116	-0.547	-0.176	0.095	-0.363	-0.006	-0.069	-0.122	-0.436	
OTHERJR	0.023	-0.231	-0.116	0.547	0.176	-0.095	0.363	0.006	0.069	0.122	0.436	
JREVDIF	0.595	0.262	-0.332	0.384	0.532	-0.481	0.243	0.23	0.041	-0.502	-0.19	
HORVELAB	0.105	-0.305	0.254	-0.024	0.09	0.377	-0.077	0.182	-0.095	0.165	0.105	

MMTDIFF HIPWRMAX KNEPWRMAX ANKPWRMAX PROTODIS OTHERJR JREVDIF HORVELAB

VJP									
TOVEL									
BCOMNET									
TRIAL									
HIPANGTO									
KNEANGTO									
ANKANGTO									
TPROP									
AVA									
AMP									
A_MECHP									
PEAKPWR									
NEGIMMAX									
HIPMMAX									
KNEMMAX									
ANKMMAX									
HIPMREV									
KNEMREV									
ANKMREV									
HIPACCPK									
KNEACCPK									
ANKACCPK									
MMTDIFF	1								
HIPWRMAX	0.141	1							
KNEPWRMAX	0.084	-0.403	1						
ANKPWRMAX	0.008	0.597	-0.148	1					
PROTODIS	0.055	0.285	-0.512	0.448	1				
OTHERJR	-0.055	-0.285	0.512	-0.448	-1	1			
JREVDIF	0.07	0.16	0.447	0.272	-0.374	0.374	1		
HORVELAB	-0.003	-0.018	0.072	-0.159	-0.109	0.109	-0.157	1	

Table H.3 Pearson correlation matrix, subject di07 (best jumper), n = 49. Variables not included were constant.

	VJP	TOVEL	BCOMNET	TRIAL	HIPANGTO	KNEANGTO	ANKANGTO	TPROP	AVA	AMP	AMECHP
VJP	1										
TOVEL	0.783	1									
BCOMNET	0.173	0.059	1								
TRIAL	-0.393	-0.52	0.058	1							
HIPANGTO	0.189	0.112	0.859	-0.141	1						
KNEANGTO	0.159	0.177	0.923	-0.112	0.793	1					
ANKANGTO	-0.002	-0.062	0.916	0.078	0.742	0.924	1				
TPROP	0.269	0.383	0.39	-0.522	0.419	0.471	0.343	1			
AVA	-0.095	-0.157	-0.4	0.429	-0.423	-0.457	-0.38	-0.97	1		
AMP	0.411	0.501	0.682	-0.359	0.586	0.735	0.578	0.824	-0.754	1	
A_MECHP	0.152	0.055	-0.457	0.3	-0.501	-0.496	-0.482	-0.859	0.932	-0.591	1
PEAKPWR	0.396	0.459	0.058	-0.064	0.048	0.133	0.022	-0.347	0.494	-0.15	0.458
NEGIMMAX	-0.477	-0.521	-0.047	0.006	-0.048	-0.052	0.058	0.068	-0.211	-0.163	-0.337
HIPMMAX	0.485	0.474	-0.205	-0.016	-0.224	-0.129	-0.216	-0.153	0.277	0.044	0.479
KNEMMAX	-0.331	-0.405	0.145	0.406	0.108	0.049	0.156	-0.223	0.138	-0.25	-0.049
ANKMMAX	-0.055	-0.195	-0.055	0.415	-0.143	-0.153	-0.044	-0.739	0.755	-0.487	0.669
HIPMREV	0.467	0.452	-0.248	-0.066	-0.243	-0.169	-0.254	-0.173	0.293	0.014	0.499
KNEMREV	-0.35	-0.427	0.124	0.414	0.053	0.042	0.17	-0.279	0.196	-0.308	-0.006
ANKMREV	0.013	-0.089	-0.124	0.355	-0.196	-0.224	-0.187	-0.65	0.667	-0.4	0.641
HIPACCPK	0.24	0.139	-0.106	-0.01	-0.116	-0.04	-0.133	-0.163	0.194	-0.109	0.252
KNEACCPK	-0.262	-0.426	-0.103	0.608	-0.169	-0.206	-0.017	-0.707	0.64	-0.613	0.474
ANKACCPK	0.159	-0.046	-0.009	0.207	-0.083	-0.042	0.061	-0.492	0.521	-0.268	0.537
MMTDIFF	0.078	0.231	-0.119	-0.38	-0.008	-0.073	-0.168	0.423	-0.386	0.256	-0.298
HIPPWRMAX	0.597	0.738	0.056	-0.447	0.099	0.17	-0.076	0.487	-0.337	0.565	-0.099
KNEPWRMAX	-0.193	-0.296	0.14	0.258	0.204	-0.104	0.026	-0.189	0.124	-0.189	-0.006
ANKPWRMAX	0.139	0.121	0.524	-0.019	0.536	0.576	0.461	0.309	-0.295	0.316	-0.397
PROTODIS	-0.069	0.076	-0.103	-0.019	0.004	-0.142	-0.199	0.302	-0.316	0.159	-0.277
OTHERJR	0.069	-0.076	0.103	0.019	-0.004	0.142	0.199	-0.302	0.316	-0.159	0.277
PRODISTA	0.031	0.033	-0.119	-0.266	0.005	-0.058	-0.102	-0.177	0.182	-0.164	0.17
OTHERVD	-0.031	-0.033	0.119	0.266	-0.005	0.058	0.102	0.177	-0.182	0.164	-0.17
JREVTDIF	0.053	0.279	-0.002	-0.168	-0.028	0.136	-0.022	0.332	-0.275	0.255	-0.24
HORVELAB	0.112	0.132	0.192	-0.046	0.142	0.237	0.237	0.197	-0.173	0.287	-0.113

	PEAKPWR	NEGIMMAX	HIPMMAX	KNEMMAX	ANKMMAX	HIPMREV	KNEMREV	ANKMREV	HIPACCPK	KNEACCPK	ANKACCPK
VJP											
TOVEL											
BCOMNET											
TRIAL											
HIPANGTO											
KNEANGTO											
ANKANGTO											
TPROP											
AVA											
AMP											
A_MECHP											
PEAKPWR	1										
NEGIMMAX	-0.362	1									
HIPMMAX	0.338	-0.487	1								
KNEMMAX	-0.116	0.074	-0.443	1							
ANKMMAX	0.378	-0.153	0.231	0.015	1						
HIPMREV	0.333	-0.482	0.985	-0.465	0.215	1					
KNEMREV	-0.086	0.08	-0.443	0.943	0.088	-0.461	1				
ANKMREV	0.284	-0.253	0.3	0.051	0.811	0.294	0.06	1			
HIPACCPK	0.245	-0.239	0.4	0.196	0.059	0.376	0.189	0.153	1		
KNEACCPK	0.207	-0.08	-0.06	0.532	0.406	-0.054	0.582	0.374	0.185	1	
ANKACCPK	0.265	-0.108	0.191	-0.069	0.496	0.179	0.03	0.118	0.036	0.279	1
MMTDIFF	-0.061	0.127	0.034	-0.385	-0.482	0.07	-0.502	-0.44	-0.259	-0.442	-0.243
HIPPWRMAX	0.18	-0.312	0.549	-0.602	-0.307	0.527	-0.644	-0.197	0.191	-0.579	-0.205
KNEPWRMAX	-0.099	0.1	-0.433	0.369	0.037	-0.417	0.263	0.051	-0.178	0.298	-0.014
ANKPWRMAX	0.241	0.024	-0.196	0.209	-0.108	-0.236	0.203	-0.146	0.183	-0.07	-0.222
PROTODIS	-0.352	0.073	-0.145	0.179	-0.501	-0.146	0.07	-0.201	0.083	-0.142	-0.604
OTHERJR	0.352	-0.073	0.145	-0.179	0.501	0.146	-0.07	0.201	-0.083	0.142	0.604
PRODISTA	0.171	-0.039	0.042	0.007	-0.069	0.109	-0.04	-0.078	0.193	0.007	0.12
OTHERVD	-0.171	0.039	-0.042	-0.007	0.069	-0.109	0.04	0.078	-0.193	-0.007	-0.12
JREVTDIF	0.174	0.049	0.085	-0.237	-0.326	0.055	-0.262	-0.231	-0.116	-0.432	-0.285
HORVELAB	0.038	0.099	-0.007	-0.118	-0.205	0.012	-0.213	-0.175	-0.099	-0.073	-0.092

MMTDIFF HIPWRMAX KNEPWRMAX ANKPWRMAX PROTODIS OTHERJR PRODISTA OTHERVD JREVDIF HORVELAB

VJP  
 TOVEL  
 BCOMNET  
 TRIAL  
 HIPANGTO  
 KNEANGTO  
 ANKANGTO  
 TPROP  
 AVA  
 AMP  
 A\_MECHP  
 PEAKPWR  
 NEGIMMAX  
 HIPMMAX  
 KNEMMAX  
 ANKMMAX  
 HIPMREV  
 KNEMREV  
 ANKMREV  
 HIPACCPK  
 KNEACCPK  
 ANKACCPK  
 MMTDIFF  
 HIPWRMAX  
 KNEPWRMAX  
 ANKPWRMAX  
 PROTODIS  
 OTHERJR  
 PRODISTA  
 OTHERVD  
 JREVDIF  
 HORVELAB

MMTDIFF	1										
HIPWRMAX	0.384	1									
KNEPWRMAX	0.027	-0.323	1								
ANKPWRMAX	-0.031	0.199	-0.079	1							
PROTODIS	0.129	0.199	0.188	0.072	1						
OTHERJR	-0.129	-0.199	-0.188	-0.072	-1	1					
PRODISTA	0.204	0.062	0.142	0.064	-0.113	0.113	1				
OTHERVD	-0.204	-0.062	-0.142	-0.064	0.113	-0.113	-1	1			
JREVDIF	0.49	0.337	-0.333	0.274	0.078	-0.078	-0.026	0.026	1		
HORVELAB	0.213	0.171	0.12	0.033	0.228	-0.228	-0.025	0.025	0.08	1	

**Table H.4 Pearson correlation matrix, subject di09 (worst jumper), n = 50. Variables not included were constant.**

	VJP	TOVEL	BCOMNET	TRIAL	HIPANGTO	KNEANGTO	ANKANGTO	TPROP	AVA	AMP	AMECHP
VJP	1										
TOVEL	0.443	1									
BCOMNET	0.347	-0.156	1								
TRIAL	-0.159	-0.276	-0.107	1							
HIPANGTO	-0.021	-0.31	0.717	-0.283	1						
KNEANGTO	-0.096	-0.023	0.67	0.024	0.56	1					
ANKANGTO	0.015	-0.239	0.875	0.061	0.67	0.765	1				
TPROP	-0.11	-0.374	0.066	0.469	-0.15	0.105	0.169	1			
AVA	0.216	0.606	-0.081	-0.505	0.06	-0.074	-0.197	-0.96	1		
AMP	0.092	-0.26	0.429	0.353	0.08	0.324	0.462	0.855	-0.803	1	
A_MECHP	0.457	0.589	-0.104	-0.415	-0.088	-0.261	-0.3	-0.822	0.863	-0.563	1
PEAKPWR	0.316	0.727	0.043	-0.429	0.017	0.083	-0.088	-0.705	0.827	-0.538	0.691
NEGIMMAX	0.056	0.045	0.312	-0.283	0.331	0.38	0.207	-0.446	0.423	-0.363	0.2
HIPMMAX	0.215	0.329	-0.178	0.186	-0.411	-0.262	-0.187	0.034	0.034	0.14	0.263
KNEMMAX	-0.341	-0.318	-0.062	-0.036	0.242	0.086	-0.053	0.045	-0.11	-0.01	-0.156
ANKMMAX	0.302	0.506	0.093	-0.542	0.089	-0.142	-0.021	-0.66	0.71	-0.456	0.658
HIPMREV	0.181	0.305	-0.157	0.267	-0.423	-0.219	-0.105	0.148	-0.075	0.237	0.145
KNEMREV	-0.311	-0.238	-0.079	-0.099	0.212	0.117	-0.086	-0.006	-0.041	-0.047	-0.088
ANKMREV	0.041	0.139	-0.069	-0.55	0.142	-0.234	-0.175	-0.433	0.408	-0.341	0.408
HIPACCPK	-0.025	0.214	-0.194	0.242	-0.182	-0.148	-0.213	-0.136	0.166	-0.074	0.251
KNEACCPK	-0.092	0.203	-0.323	0.052	-0.268	-0.081	-0.33	-0.324	0.339	-0.385	0.281
ANKACCPK	0.137	0.142	-0.035	-0.059	-0.038	-0.083	-0.139	-0.069	0.087	-0.002	0.175
MMTDIFF	-0.047	0.138	-0.069	0.367	-0.09	0.271	-0.051	0.34	-0.249	0.237	-0.289
HIPPWRMAX	0.433	0.413	0	0.174	-0.375	-0.02	-0.04	0.068	0.059	0.08	0.129
KNEPWRMAX	-0.019	-0.251	0.281	-0.325	0.537	-0.157	0.225	-0.263	0.159	-0.101	0.168
ANKPWRMAX	0.146	0.543	0.138	-0.269	0.089	0.511	0.115	-0.406	0.516	-0.315	0.306
PROTODIS	-0.295	-0.174	-0.11	-0.046	0.095	0.105	-0.062	-0.014	-0.026	-0.093	-0.118
OTHERJR	0.295	0.174	0.11	0.046	-0.095	-0.105	0.062	0.014	0.026	0.093	0.118
JREVTDIF	-0.098	0.024	-0.048	-0.392	0.293	0.029	-0.074	-0.07	0.085	-0.125	-0.01
HORVELAB	-0.089	-0.402	-0.022	0.202	-0.026	-0.16	0.024	0.018	-0.14	-0.045	-0.101

	PEAKPWR	NEGIMMAX	HIPMMAX	KNEMMAX	ANKMMAX	HIPMREV	KNEMREV	ANKMREV	HIPACCPK	KNEACCPK	ANKACCPK
VJP											
TOVEL											
BCOMNET											
TRIAL											
HIPANGTO											
KNEANGTO											
ANKANGTO											
TPROP											
AVA											
AMP											
A_MECHP											
PEAKPWR	1										
NEGIMMAX	0.371	1									
HIPMMAX	0.068	-0.317	1								
KNEMMAX	-0.202	-0.121	-0.504	1							
ANKMMAX	0.653	0.212	0.17	-0.344	1						
HIPMREV	0.004	-0.378	0.949	-0.551	0.103	1					
KNEMREV	-0.123	-0.065	-0.512	0.966	-0.306	-0.56	1				
ANKMREV	0.215	0.147	0.092	-0.284	0.651	0.014	-0.271	1			
HIPACCPK	0.114	-0.15	0.465	0.06	-0.014	0.437	-0.008	-0.202	1		
KNEACCPK	0.27	-0.006	0.008	0.066	0.147	-0.056	0.103	0.09	0.222	1	
ANKACCPK	0.103	-0.131	-0.145	0.374	0.092	-0.104	0.44	-0.118	0.093	0.153	1
MMTDIFF	-0.03	-0.027	0.035	0.189	-0.48	0.008	0.191	-0.638	0.277	0.098	-0.063
HIPPWRMAX	0.26	-0.048	0.372	-0.437	0.147	0.346	-0.423	-0.044	-0.164	0.171	-0.149
KNEPWRMAX	-0.026	0.037	-0.216	0.124	0.354	-0.23	0.073	0.373	0.034	-0.335	0.082
ANKPWRMAX	0.601	0.426	-0.022	-0.114	0.319	-0.083	-0.012	-0.004	0.049	0.329	0.026
PROTODIS	-0.101	0.212	-0.06	-0.101	-0.094	-0.101	-0.143	0.38	-0.029	0.203	-0.465
OTHERJR	0.101	-0.212	0.06	0.101	0.094	0.101	0.143	-0.38	0.029	-0.203	0.465
JREVTDF	0	0.128	0.025	0.118	0.086	-0.082	0.027	0.306	0.047	-0.134	-0.274
HORVELAB	-0.351	-0.137	-0.183	0.26	-0.173	-0.233	0.194	-0.015	-0.07	0.064	0.051

MMTDIFF HIPPWRMAX KNEPWRMAX ANKPWRMAX PROTODIS OTHERJR JREVDIF HORVELAB

VJP									
TOVEL									
BCOMNET									
TRIAL									
HIPANGTO									
KNEANGTO									
ANKANGTO									
TPROP									
AVA									
AMP									
A_MECHP									
PEAKPWR									
NEGIMMAX									
HIPMMAX									
KNEMMAX									
ANKMMAX									
HIPMREV									
KNEMREV									
ANKMREV									
HIPACCPK									
KNEACCPK									
ANKACCPK									
MMTDIFF	1								
HIPPWRMAX	0.086	1							
KNEPWRMAX	-0.441	-0.489	1						
ANKPWRMAX	0.248	0.282	-0.33	1					
PROTODIS	0.038	0.022	-0.119	0.062	1				
OTHERJR	-0.038	-0.022	0.119	-0.062	-1	1			
JREVDIF	0.084	-0.118	0.125	0.146	0.273	-0.273	1		
HORVELAB	-0.192	-0.025	0.143	-0.341	-0.009	0.009	-0.186	1	

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