An Examination of Relative and Absolute Timing in Children, Adolescents, and Adult Vertical Jumpers

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CHAPTER ONE:
Introduction

The act of jumping is one of several fundamental skills developed during childhood and later used in many sport activities. A basketball player jumping to get a rebound, a volleyball player attempting a spike, or a wide receiver attempting to catch a pass over a defensive back in football are all examples of how jumping ability is essential to sport performance. Jumping ability is so important that it is widely used as part of a testing battery to predict the performance of athletes. There is no disputing the fact that strength is related to one's ability to perform this motor skill. However, there are other factors, such as coordination and timing of the movement that are also important to jumping height (Jensen, Phillips, & Clark, 1994).

Jumping with the goal of achieving maximum vertical displacement, referred to as vertical jumping, requires strength and coordination. Children will first begin to propel themselves into the air in a jumping movement sometime after the age of two years (Jensen et al. 1994; Gallahue and Ozmun, 2006). Although a young child and a skilled athlete are able to accomplish the same movement goal of jumping for height, differences exist in the efficiency between the novice and experienced jumper. Differences between novice and experienced performers are often times recognized by performance variables such as jumping height or distance. However, jumping ability can also be described according to coordination variables that include timing of limb segments, initiation of joint reversals, length of push-off or propulsive phase, and control variables that include joint angles at certain points in the movement. A few studies have examined factors other than strength that relate to improved performance. Clark, Phillips, & Petersen (1989) noted differences between experienced and non-experienced jumpers. They found significantly higher angular velocity values of the knee joint during standing long jump for volleyball players and gymnasts (685 and 700 degrees/second) compared to children ages 3, 5, 7, and 9 years (325, 400, 425, and 440 degrees/second respectively). Clark & Phillips (1985) found a progressive pattern for arm action in the standing long jump from age 3 to 7 years. The patterns began at age 3 with no arm action, progressing to flexion only at takeoff, shoulder hyperextension during the crouch, and finally, hyperextension and full (greater than 160 degrees) flexion during flight. Jensen, Phillips, and Clark (1994) determined that children can be separated for efficiency in the vertical jump based on the consequences of takeoff angle. Lower takeoff angle jumpers achieved less vertical displacement and reached take-off prematurely in the jumping cycle compared to high takeoff angle jumpers. Jensen, et al. concluded that the differences were indicative of decreased strength for the low angle jumpers. They also hypothesized those other control mechanisms related to balance and controlling the mass of the trunk during countermovement and push-off phases were contributing to the differences.

A relatively new way to examine skill progression is a dynamic systems or constraints approach to skill acquisition. Constraints may be any potential factor that might alter the process or outcome of a movement. Constraints are the result of three primary sources: 1) individual; 2) environment; and 3) goal of the task (Newell, 1985). Constraints set boundaries or limits on motor patterns and guide the motor system toward new patterns. Individual constraints would be personal characteristics such as strength of the individual or the development of the nervous system itself. Jumping that occurs during a sporting competition is highly variable due to changes in body posture as well as the goal of the movement. For example, a volleyball player going to spike a set-up pass from their teammate must adjust the jump to changes in base of support (or width of foot placement) and the extent of their crouched position (joint angles of hip extension and knee flexion). The athlete must make an immediate adjustment to the exact direction forces are applied to the ground in order to contact the ball at the apex of the jump. In this particular case, both environmental and goal constraints would cause extemporaneous 'real-time' changes in pattern of jump. Dynamic systems perspective indicates that the body will self-organize in order to perform the most efficient motor pattern within given constraints on the system. That is, the motor system will exploit the degrees of freedom for a movement within the system's constraints. Degrees of freedom refer to all the possible ways a movement can be performed (Bernstein, 1967). Early performers tend to isolate choices for completing a movement and do not utilize all the degrees of freedom available. Based on degrees of freedom and constraints, the motor system will organize a neurological strategy to form a synergy or coordinative structure. Coordinative structures are neural processes which entrain certain muscle groups to act as a unit in order to accomplish a movement goal (Thelen, 1994).

Coordinative structures may be identified by the relative position or timing of limb segments that occur during a movement. Relative timing refers to the timing of limb segments from a common identifiable point to an important event during the movement. Consistent relative timing with a change in the metrics or rate of a movement is an indication that a coordinative structure exists. Coordinative structures may change resulting in a different movement pattern if a constraint is scaled to a critical value and becomes a control parameter (Jensen, et al. 1994; Clark, et al. 1989). Control parameters are defined as a constraint that when scaled to a sufficient value will influence the stability of a motor pattern (Thelen, 1994). New patterns that form are influenced by an order parameter. The order parameter is a mechanical principle that allows the systems segments to organize into a particular motor pattern (Kelso, 1991). In addition, how well the order parameter is exploited dictates the skill level of the performers. Optimal exploitation of an order parameter by a biological system allows for the most efficient pattern to take place for a given movement. For example, Southard (2006, In Press) found that for the skill of throwing exploiting the open kinetic chain by scaling up on velocity of throw provided for optimal lag times between arm segments and the most efficient movement. Since jumping is a closed kinetic chain skill when forces are exerted, the order parameter is balance and the ability to control the trunk in relation to lower body segments (Jensen, et al. 1994).

The force applied to the floor has been identified as a control parameter for jumping (Jensen, et al. 1994). Mechanical variables related to balance such as controlling the location of the mass of the trunk relative to lower limb segments during the crouching and extension phase is the order parameter for jumping. The order parameter determines the level of performance in the standing long jump (Jensen, et al. 1994). Jensen, et al. (1994) proposed different levels of performance for the jump. They determined that a mature motor pattern is marked by complete extension of the ankles, knees, and hips at takeoff. Clark & Phillips (1985) supported the Jensen et al. (1994) results for the standing vertical jump. A typical mature jumping pattern is identified when the trunk reverses direction in upward rotation while the lower body segments and joints are still undergoing flexion or have reached their maximal negative displacement and flexion values at low point of crouch. The trunk reaches peak velocity first followed in sequence by the hip, knee, ankle, and foot (Clark, et al. 1989). The proximal-to-distal sequence identifies a mature coordinative structure for jumping.

CHAPTER TWO:
Literature Review

Strength and Jump Performance

Knee extensor strength is widely accepted as a constraint in jumping performance. This is not surprising given the control parameter for jumping is the application of force (Jensen, et al. 1994; Bobbert, et al. 1996; Bosco, et al. 1982). For example, Paasuke, Ereline, and Gapeyeva (2001) found that vertical jump performance in pre-pubertal boys was 15% less than post-pubertal boys. The authors proposed that this decrement in jump height for pre-pubertal boys was due to less quadriceps strength. Strength tests in the study showed maximal isometric force and rate of isometric force development of the quadriceps to be substantially less in pre-pubertal boys compared to post-pubertal boys. Feltner, Bishop, and Perez (2004) also identified increasing the average amount of ground reaction forces exerted during push-off phase as one of the two ways of increasing vertical velocity of the center of mass at takeoff. Increasing the velocity of the center of mass at takeoff will ultimately lead to greater performance. Therefore, increasing velocity of the trunk to a value of 3 m/s or greater is of paramount importance to the skill of jumping. The authors identified an additional means of increasing vertical velocity by increasing the length of time between low point and takeoff, or propulsive phase. The increase in time should relate to a greater impulse produced and a greater velocity at take-off.

Tomioka, Owings, and Grabiner (2001) found that isokinetic knee extensor strength at 60 degrees per second was significantly correlated with vertical jump height ($r = .76$, $p = .004$). However, maximal knee extensor isometric strength and isokinetic strength at 150 and 240 degrees per second showed no significant correlation with vertical jump height. The authors concluded that the coordination utilized in a knee extension at high velocities will not necessarily transfer to a dynamic movement such as vertical jump. The same study showed a significant correlation between vertical jump height and phase angles of the hip and knee during propulsion phase ($r = .71$, $p = .01$). Phase angles were used in the study as one measure of coordination between hip and knee for the vertical jump. The authors concluded that because coordination is of equal or more importance than strength, increasing quadriceps strength did not automatically translate to improved kinematics or maximum efficiency.

Coordination and Jump Performance

Relative time to peak velocity of the trunk, illiac crest, lateral epicondyle, lateral malleolus, and 5^{th} metatarsal phalangeal joint from movement in y axis to take-off has been shown to remain consistent in both young and adult jumpers (Jensen, et al 1994; Clark, et al. 1989). Relative time for jumping refers to the time elapsed between peak velocity of data points or limb segments relative to an important identifiable point in the movement such as take-off. The proximal to distal sequence of time to peak velocity represents the pattern of coordination for the vertical jump (Jensen, et al. 1994; Clark, et al. 1989; Hudson, 1986). While the relative coordination of segments remains constant for children and adults, there are differences in jumping height due to differences in strength and balance. Young jumpers fail to fully exploit the order parameter and do not possess the leg strength of adults during execution of a vertical jump. Jensen, Phillips, and Clark (1994) found causal factors for reduced performance in young jumpers. While coordination, (relative timing between limb segments) remained unaltered, other variables such as position and magnitude showed differences across age. Magnitude variables refer to peak angular velocity values at important times during the movement, while position variables refer to segmental and joint angles at important points in the jump. It may be that the absolute timing of segments is different across age even though relative timing remains constant. Absolute timing refers to the time between peak velocity of segments or the rate at which the pattern is executed within a consistent relative pattern. Achieving optimal absolute time values for the trunk and lower limbs is a strategy for achieving maximal jump height and may be a signature for an efficient jumping pattern.

Hudson (1986) found that 17 out of 20 adult skilled jumpers had 'simultaneous' patterns of coordination in the vertical jump. That is, the selected data points all reached peak angular velocity in a proximal to distal fashion with non-significant time delays. Hudson hypothesized that the relationship in absolute timing between the trunk and thigh was of paramount importance, and possibly more important than the relationship between other segments. The temporal variable of delay between maximum velocity in the trunk and thigh showed significance ($P < .05$) and was 53 milliseconds when averaged between all 20 subjects with a standard deviation of 74 milliseconds. However, Hudson hypothesized that once absolute timing values reach 20 milliseconds, decreasing the time between peak velocities would result in little to no improvement in performance and be nearly impossible to measure. Hudson also proposed that insufficient strength of the vastus lateralis muscle was a plausible explanation for the differences in the absolute timing. Lack of quadriceps strength allowed for less utilization of stored elastic energy built up from the eccentric crouching phase of the jump. Another possible reason stated for lower elastic energy use was an unforeseen surge of force at the time of amortization

(Hudson, 1986). It appeared that the less skilled jumpers were unable to control the trunk optimally at the time of amortization to direct forces vertically. Jensen, et al. (1994) had similar findings in the inability to direct forces vertically for low takeoff angle jumpers indicated by a more vertical position of the shank with less ankle dorsiflexion in high takeoff angle jumpers.

Although Hudson analyzed differences in absolute timing, skill level was based on “effective integration of the legs” (EIL). Effective integration of the legs referred to the time delays between initiation of extension in the trunk and lower limb segments, rather than delays in peak angular velocity. From these time differences in joint extension, a percentage was derived in which the amount of time that 2 or more segments were positively contributing to the movement was determined (i.e.: undergoing extension). If a participant spent more than 50% of their movement time in positive shared contribution for two or more segments, they were said to have a ‘simultaneous pattern’. Delay times between initiations of extension in the most skilled jumpers were non-significant, less than 25 milliseconds between extension of the trunk/thigh and thigh/shank. For the least skilled subjects, delays between initiations of extension were greater than 60 milliseconds ($P < .05$), and at times were not proximal to distal in order. It is important to mention that Hudson (1986) did not allow for arm swing during jumping, she required participants to keep the hands in contact with the hips throughout the entire movement. Lack of arm integration could have affected not only jumping height, but the relative timing of the trunk and lower limbs. Arm swing during jumping has been shown to increase displacement and vertical velocity of the center of mass at takeoff (Feltner, et al. 2004). Lees, et al. (2006) found that 16% of the total work performed during a vertical jump came from the contribution of the arms due to increased storage and release of elastic energy in the lower body segments.

Whereas Hudson (1986) termed a mature jumping pattern 'simultaneous' based on amount of time spent in extension between segments, Hagenauer, Legreneur, and Monteil (2005) found a different type of simultaneous pattern in elderly jumpers. The researchers analyzed kinematic differences between the vertical jumps of young (18-25 years) and elderly men (79-100 years). It was found that while young men exhibited the proximal-distal order of reaching peak linear velocity, elderly men reached peak relative velocity of the trunk, hip, knee, and ankle at the exact same moment in time. Also, the time at which the peak linear velocity values were reached was earlier in the push-off phase relative to when young men reached peak velocity of data points. The authors attributed the differences in temporal coordination to factors other than strength because the elderly men had already reached higher hip extension angles and their final angular position prior to takeoff. Haguenauer, et al. suggested that rigidity of the system due to a higher co-contraction level in the elderly caused the differences in coordination. It may be that co-contraction is a constraint which lessens the extent to which one can exploit the order parameter.

Strength and coordination may be independent contributors in achieving maximal jumping height. Domire and Challis (2007) found that increasing the amount of hip and knee flexion, or crouch depth did not result in higher vertical jump. Despite a simulation model which showed that increasing squat depth would increase the time over which force could be applied, jump heights were the same for preferred countermovement and deep squat positions. The authors found that ground reaction force curves with abnormal patterns as well as lower values of 1600-1800 Newtons for the deep crouch group compared to 2200 Newtons for the preferred crouch depth group. Although kinematic data was not obtained, reasons attributed to lack of performance increases with a deeper crouch were the lack of ability to coordinate the deeper joint angles and optimally control the longer push-off phase.

The purposes of this study were to determine: 1) the timing of joints and segments relative to takeoff across age; 2) the absolute timing of limb segments across age; 3) the amount of time spent in eccentric countermovement of concentric push-off phases across age groups; 4) if joint angles at common identifiable points in the movement change across age groups; and 5) if performance (height jumped) changes across age groups. Results should provide data for the identification of changing jumping dynamics across age.

It is hypothesized that: 1) relative timing of joints and segments with respect to initiation of movement will remain constant; 2) relative timing of joints and segments with respect to take-off will remain constant; 3) absolute timing (segmental lag between adjoining segments) will be less for adults than for adolescents and children; 4) adults will spend more time in both countermovement and push-off phases than adolescents and children; 5) adults will experience greater hip and knee joint flexion at the depth of countermovement than adolescents or adults; 6) adults will jump significantly ($P < .05$) higher than adolescents or children.

CHAPTER THREE:
Method

Participants

Participants were 27 males without any medical condition that might inhibit vertical jump performance. The 27 participants ranged in age from 4 years to 24 years (8, 4-6 year olds; 9, 12-14 year olds; and 10, 20-24 year olds). Recruitment was by word of mouth. Participation was voluntary with no incentives. Written consent was obtained from 20-24 year old participants. Verbal consent was obtained from children and adolescents along with written consent from parents or guardians.

Instruments

A Peak motion analysis system was used to collect and digitize data. Two digital cameras (60 Hz) captured participants' motion during a vertical jump. One camera was placed 5 meters from the participant and perpendicular to the principle axis of motion (X axis). A second camera was placed 5 meters behind and directly in line with participants. The combined cameras provided kinematic data in 3 axes (X, Y, and Z). Both cameras were placed on a tripod at 2.5 meters from the floor. The system was calibrated with a 16 point calibration frame. The cameras were synchronized with a remote audio sensing unit. Direct linear transformation calculated 3D data from the multiple 2D views. Light reflective markers were placed on the following five data collection points which represented the trunk and lower-body joints: 12^{th} rib (trunk), greater trochanter (hip joint), lateral epicondyle (knee joint), lateral malleolus (ankle joint), and 5^{th} metatarsal phalangeal joint (foot). Flood lights were used to illuminate and help identify the data points during digitization. The data points were digitized automatically using Peak software.

Procedure

Participants, including parents of young participants, reported to the Motor Behavior Laboratory. Each participant completed stretching exercises and three practice jumps for warm up. Previous research (Burkett, et al. 2005) indicates that a warm up specific to vertical jump results in a more accurate vertical jump height. Following warm up, each participant completed five jumps for maximum vertical height. No instruction or feedback was given to the participants regarding the pattern of jumping. The only instruction was to jump as high as possible. Participants received 60 seconds of rest between jumps. For older participants, only the researchers were present in the lab during data collection.

Analysis

This study utilized a between groups design. The independent factor of group was determined by the age of participants. Group 1 was adults (20-24 years), group 2 were adolescents (12-14 years), and group 3 was children (4-6 years). There were eight dependent variables: 1) time to peak linear velocity of each data point relative to takeoff; 2) time to peak angular velocity of joints relative to takeoff; 3) peak velocities of each segment; 4) absolute timing or segmental lag between adjoining segments; 5) maximal joint flexion angles at depth of crouch; 6) time to low point of crouch or countermovement phase; 7) time of push-off phase prior to takeoff; and 8) height jumped. The phase times (countermovement phase and propulsive phase) were determined by digitizing displacement of the hip joint marker during the jump. Time spent in countermovement phase was defined as the time between initiation of movement and takeoff. Initiation of movement was said to start after .01 meters of displacement by the hip joint. Time spent in push-off phase was defined as the time between maximal negative displacement of the hip joint and takeoff. Takeoff was determined during digitizing as the frame in which the feet left the ground. Data was analyzed using one-way MANOVA for dependent measures one through seven. Follow up ANOVA indicated specific variables responsible for significance. Univariate ANOVA determined any significance between groups for dependent measure of height jumped. Scheffe post hoc comparison determined means responsible for significance. Partial correlation was completed to indicate relationships between selected dependent measures and height jumped. An alpha level of .01 was selected to account for sphericity violation. Omega square was used to indicate effect size following MANOVA and ANOVA.

Chapter Four:
Results

Relative Timing

Time to Peak Linear Velocity Relative to Takeoff

MANOVA indicated a significant main effect by group (Wilk's $\lambda = .522$, $F(10, 246) = 9.46$, $P < .01$, $\omega^2 = .08$). Follow up ANOVA indicated that all five data points (trunk, greater trochanter, lateral epicondyle, lateral malleolus, and small toe) were responsible for significance. Post hoc analysis indicated that for the trunk the children were significantly greater than adolescents and adults with no significant differences between the adults and adolescents. For the hip, the children and adolescents experienced significantly greater time than adults. For the knee, children experienced a mean positive value which was significantly greater than the negative values of both adolescents and adults. For the ankle, children had less negative values than both remaining groups which were not significantly different from each other. For the foot, the children had significantly less negative time than both remaining groups. Generally, the adolescents and adults experienced similar times with the children responsible for significant differences. See Figure 1 for a graphic representation means by group and data point.

Time to Peak Angular Velocity Relative to Takeoff

MANOVA indicated no significant main effects by group. However, qualitative differences existed with regard to sequencing of the lower body joints (hip, knee, and ankle). Adults and adolescents both demonstrated a proximal-to-distal pattern of angular velocities for the lower body joints. That is, the hip joint reaches peak velocity first, followed by the knee, and finally the ankle prior to takeoff. In children however, the ankle reached peak angular velocity .01 seconds before the knee, possibly indicating premature plantar flexion. See Figure 2 for a graphic representation of means by group and data point.

Peak Velocity

MANOVA indicated a significant main effect by group (Wilk's $\lambda = .073$, $F(10, 246) = 66.51$, $P < .01$, $\omega^2 = .13$). Follow up ANOVA indicated that all five data points (trunk, greater trochanter, lateral epicondyle, lateral malleolus, and small toe) were responsible for significance. Post-hoc analysis indicated that for the trunk and hip adults reached higher velocities than adolescents and children, with adolescents attaining greater velocities than children. For the knee, ankle, and foot adults and adolescents were greater than children. See Figure 3 for a graphic representation of means by group and data point.

Absolute Timing/Segmental Lag

MANOVA indicated significant main effect by group (Wilk's $\lambda = .823$, $F(8, 248) = 3.18$, $P < .01$, $\omega^2 = .09$). Follow-up Anova indicated segmental lag for the hip, knee, and ankle were responsible for significance. Post-hoc analysis indicated that for the hip adolescents had less negative values than children. For the knee and ankle, children had less negative values than adolescents. Absolute timing indicates negative values for all distal data points, affirming a proximal-to-distal joint velocity indicated in previous research (Hudson, 1986). See Figure 4 for a graphic representation of means for absolute timing.

<u>Countermovement Phase</u>

Time to Low Point

MANOVA indicated significant main effect by group (Wilk's $\lambda = .744$, $F(6, 248) = 6.54$, $P < .01$, $\omega^2 = .16$). Follow-up Anova indicated that all three variables (trunk, hip, and knee) were responsible for significance. Post hoc analysis indicated that for the trunk, hip, and knee adults and adolescents took more time in the countermovement phase than children. See Figure 5 for a graphic representation of means.

Joint Angle at Low Point

MANOVA indicated a significant main effect by group (Wilk's $\lambda = .755$, $F(6, 250) = 6.28$, $P < .01$, $\omega^2 = .14$). Follow up Anova indicated the hip and knee joints were responsible for significance. Post-hoc analysis indicated that for the hip and knee joints adolescents and children displayed greater flexion than adults. Joint angles were determined as a static measure at the low point of countermovement. See Figure 6 for a graphic representation of means.

<u>Propulsive Phase</u>

MANOVA indicated a significant main effect by group (Wilk's $\lambda = .791$, $F(6, 248) = 5.15$, $P < .01$, $\omega^2 = .11$). Follow up Anova indicated that all three variables (trunk, hip, and knee) were responsible for the significant main effect. Post hoc analysis indicated that for the trunk, hip, and knee adults took significantly longer in the propulsive phase than children. See Figure 7 for a graphic representation of means.

<u>Height Jumped</u>

One-way Anova indicated a significant main effect between groups ($F(2, 130) = 236$, $P < .01$, $\omega^2 = .23$). Post-hoc analysis indicated significant differences between all three. Adults were the highest jumpers followed, in order, by adolescents and children. See Figure 8 for a graph of mean heights.

Correlational Data

Zero-order correlations indicated strong relationships between the peak linear velocity of each segment and height jumped (Trunk r = .933; hip r=.936; knee r = .944; ankle r = .902; and foot r = .864). Stepwise multiple regression was used to determine segments that were the best predictors of height jumped. Results indicated that peak velocity of the knee was the best predictor and was responsible for 89% of the variance (Adjusted $R^2 = .891$, $F (1,128) = 1051.49$, $P < .001$).

Phase-Plane Analysis

Phase-plane diagrams were completed for a qualitative analysis of jumping pattern across age groups. A phase-plane provides a graphic representation of displacement and velocity on separate axes to indicate the activity of a data point. The shape of the phase-plane is an indication of the movement pattern. Phase-planes that are represented across a number of trials may represent variation in pattern. That is, the more disparate the shape the greater the variation across trials. The phase-planes represented in Figures 9, 10, and 11 are the displacement and velocity of the knee during the jumping cycle. Note that the consistency of performance decreases as the age of participants decreases.

CHAPTER FIVE:
Discussion

The hypothesis that the relative timing of the trunk and joint peak velocities with respect to movement initiation will remain constant across age groups was supported. That is, all three age groups reached peak linear velocity in a proximal-to-distal order. This finding is consistent with previous research concerning jumping coordination (Clark, et al. 1989, Jensen, et al. 1994). Consistency in relative timing provides evidence for similar coordination strategies across age groups despite differences in performance. That is, there was consistent relative timing of limb segments across changes in the metrics of movements (Kelso, Southard, Goodman, 1979) experienced across age groups. The trunk reached peak velocity first followed by the hip, knee, and ankle joints for all age groups. The suggestion that timing, force, and rate are separate components of coordination (Kelso, 1981), was supported by the results of this study. Rate refers to how early in push-off phase peak velocities were reached and the overall amount of time spent in countermovement and push-off phases. The adults spent significantly longer in countermovement and propulsive phases than children, while children reached peak velocities earlier in propulsive phase. The differences in rate likely caused qualitative changes in timing relative to takeoff as well as differences in segmental lag but did not alter the proximal-to-distal coordination pattern.

The hypothesis that relative timing with respect to takeoff would remain constant across age groups was not supported. Differences were significant across ages relative to segments reaching peak velocity prior to takeoff. For all ages, the trunk and hip reached peak velocity prior to takeoff, while for children the knee also reached a peak velocity before takeoff. The differences do not indicate a separate coordinative structure, but may indicate differences in constraints such as strength, balance, and motivation (Jensen, Phillips, & Clark, 1994). It may be that children have reached the strength needed to achieve takeoff while other constraints such as balance have not yet reached levels needed for peak efficiency.

The hypothesis that absolute timing of limb segments would differ across age groups was supported. Significant differences ($P < .05$) were found between adolescents and children for segmental lag of the hip, knee, and ankle. For the hip, delay times relative to the trunk were greater ($P < .05$) for children than adults and adolescents. For the knee and ankle, delay times relative to the next proximal joint (hip and knee) were greater ($P < .05$) for adults and adolescents than children. Whereas significant differences were found, all lag values were 40 milliseconds or less for joints relative to their proximal neighbor. Hudson (1986) proposed that delay times of 60 milliseconds or greater for segmental lag would cause decrements in jumping efficiency or performance. The three age groups in this study achieved less than 60 milliseconds for all delay times of segmental lag. The significant differences may be an indication that adults are maximizing the mechanical principle related to jumping. For example, maintaining balance of the trunk would allow jumpers to take mechanical advantage of increasing the velocity of each joint before takeoff. Previous research by Clark, et al. (1989) found that skilled long jumpers used the strategy to increase delay times compared to unskilled jumpers. Increasing delay times refers to lengthening the absolute time between peak velocities of a proximal segment relative to a distal segment. Clark, et al. proposed that the ability to control the trunk allowed for a more inclined position of the trunk at takeoff to help the jumper achieve the task of maximum horizontal displacement. Haguenauer, et al. (2005) compared jumping kinematics between young (18-25 years) and elderly (79-100 years) men and found differences in absolute timing or segmental lag delays. The jumpers 18-25 years displayed proximal-to-distal order of peak velocity similar to adults and adolescents in this study. The elderly men, however, displayed a simultaneous pattern for the trunk and lower body joints with all points reaching peak velocity at the same point in time or within 10 milliseconds of one another. The absolute timing of the elderly men closely resembles that of children in this study. That is, children experienced less segmental lag between the hip & knee, and knee & ankle compared to adolescents and adults. This likely is the result of similar constraints on the elderly and young. Haguenauer et al (2005) suggested that high amounts of co-contraction caused rigidity of the lower body and was responsible for causing the simultaneous peak velocities. Co-contraction would contribute to lower force production and could be a constraint common to both young children and the elderly.

The hypothesis that time spent in countermovement and push-off phases would differ across age groups was supported. Based on time to low point of the hip joint, children spent an average of 90 milliseconds less time in the countermovement phase than adolescents ($P < .05$), and an average of 130 milliseconds less time than adults ($P < .05$). The increase in time to reach maximum squat depth for adults is consistent with increases in joint flexion during the countermovement phase. For time spent between low point and takeoff, adults took an average of 100 milliseconds longer ($P < .05$) than children. Increasing the amount of time spent in propulsive phase is an effective strategy for increasing vertical velocity at takeoff (Feltner, et al, 2004). The increased amount of countermovement time likely aided the adults' ability to increase the impulse produced during the propulsive phase. Pandy & Zajac (1991) indicated that longer absolute time spent in the propulsive phase allows ankle plantarflexors to be activated during the last 20% of the jump thereby increasing the angular velocity of the foot. Pandy & Zajac also found that activating the plantar flexors in this manner maximized the overall amount of energy contributed to the trunk (30%) at takeoff. In this study, there were differences in peak angular velocity of the ankle joint between adults and children, and adolescents and children. Figure 2 shows that for children the ankle joint reaches its peak angular velocity prior to the knee, while for adults and adolescents the ankle joint follows the hip and knee joints. The improper timing for peak velocity of the ankle in children indicates that they contract the gastrocnemius and soleus muscles too soon. Bobbert and Schenau (1988) indicated that proper contraction timing of the gastrocnemius was crucial to jumping performance because it is a bi-articular muscle. A bi-articular muscle is one that spans across two joints, in the case of the gastrocnemius, across both the knee joint and the ankle. The fact that a bi-articular muscle spans across two joints forces it to act as both a flexor and extensor simultaneously during some multi-joint movements, making it more important for the muscle to fire at the appropriate time.

The hypothesis that joint angles of the hip and knee would differ during countermovement was supported. On average, adults experienced a greater range of motion at the hip ($P < .05$) than adolescents and ($P < .05$) children. Average knee flexion at the low point of the countermovement, was 13 degrees more for adults than adolescents ($P < .05$) and 9 degrees more for adults than children ($P < .05$). A previous study by Domire & Challis (2007) compared kinematics and performance of a computer simulated model to participants for jumps started from different depths. For the computer simulation, the optimum squat depth was the lowest position. Participants, however, experienced lower jump heights after increasing countermovement depth by 28 degrees at the hip and 20 degrees at the knee. Domire and Challis hypothesized that participants were not able to coordinate when and how much force to exert during push-off following the deeper countermovement. For this study, the ability of the adults to obtain larger ranges of motion may be due to the anatomical differences of the thigh and shank compared to children. A larger femur in the adults would allow for a mechanical advantage in exerting force over a longer period of time. With an increased radius of rotation, the adults were able to increase overall force production (Hay, 1993). In addition, the increased hip flexion of the adults would allow for more forward rotation of the trunk during countermovement, which would result in an increased ability to produce force when the trunk reverses to extension and backward rotation.

The hypothesis that adults would jump significantly higher than adolescents and children was supported. Extensor strength has been identified (Jensen, Phillips, & Clark, 1994) as a control parameter for jumping. Although force was not directly measured in this study, differences in peak velocity of the trunk and knee indicate larger amounts of force are applied during the propulsive phase. Certainly the increased time spent in the propulsive phase and greater range of motion would contribute to the increase in force production. The peak velocities of both the trunk and the knee were 1.5 m/s faster for adults and adolescents than children. With extensor strength as a control parameter, it is likely that increases in extensor strength are responsible for changes in propulsive time and greater range of motion.

Analysis of phase-planes provides qualitative evidence for the stability of pattern across age groups. Whereas, quantitative differences in phase-plane patterns were not determined – a visual inspection indicates that variability in jump pattern increases as age decreases. The stability of pattern for adults and adolescents compared to children may indicate that maximal forces are being exerted consistently relative to takeoff (Figures 9, 10, and 11). Child jumpers however, experienced variability in pattern which indicates possible differences in the time of force application across trials.

Results of this study support earlier findings (Clark, et al. 1989; Jensen, Phillips, & Clark, 1994) that relative timing remains constant while control factors such as joint angles and peak velocities change across different ages. While relative timing with respect to the start of propulsive phase remained constant across age groups, timing relative to takeoff differed across age groups. Correlational results from this study indicate that coordination and control variables are related. For example, time spent in the countermovement phase, a coordination variable, was significantly related to the control variables of segmental lag of the thigh ($r = -.201$), joint angles of the hip ($r = -.571$) and joint angle of the knee ($r = -.482$) at the low point of the countermovement. Whereas, there are measurable relationships between coordination and control variables, the causal relationship between the two factors remains unclear. Future studies should systematically vary the muscle forces exerted during the jump to determine their effect on jumping pattern. Such a strategy may provide evidence for the effect of force output and other control variables on pattern change.

Summary

Results of this study have both theoretical implications and practical application to the skill of vertical jumping. From a practical standpoint, data indicates that strength and coordination are crucial to jumping performance and require attention in order to improve vertical jumping. In addition, further research is needed to determine the best way to practice jumping in order to improve a specific sport skill. From a dynamic systems perspective performers should practice in an environment similar to their sport situation. Data from this study indicates that segmental lag and time spent in phases of the jump performance should be used to identify jumping level. Theoretically, future research should systematically vary the force exerted by jumpers of different ages in order to determine if force is a control parameter that allows jumping patterns to change.

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Figure Captions

Figure 1: Time to Peak Velocity
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. Note that for group 3 (children) there are 3 points (trunk, hip, and knee) that reach peak velocity prior to takeoff. In adults and adolescents only 2 points (trunk, hip) reach peak velocity prior to takeoff. All five points (trunk, greater trochanter, lateral epicondyle, lateral malleolus, small toe) were responsible for significant main effect by group ($P < .01$).

Figure 2: Peak Linear Velocity
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. Peak linear velocity values of each data point across groups. Note the higher values for all data points in adults and adolescents vs. children. All five data points (trunk, greater trochanter, lateral epicondyle, lateral malleolus, small toe) were responsible for significant main effect by group ($P < .01$).

Figure 3: Time to Peak Angular Velocity

Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. All data points reach peak angular velocity values prior to takeoff. Note that in children (group 3), the ankle joint reaches its peak value prior to the knee joint. There was no significant main effect by group, but there were qualitative differences by group. In children, the ankle joint reaches peak velocity prior to the knee joint, not following the same proximal-to-distal pattern found in adolescents and adults.

Figure 4: Absolute Timing/Segmental Lag (Linear)
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. The graph represents the amount of time in seconds between peak velocity of one data point relative to the next distal point. Negative values indicate the distal point lagging behind its proximal neighbor. For example, for group 1 (adults) the hip reaches peak velocity 20 milliseconds after the trunk. Segmental lag of the hip, knee, and ankle were responsible for significant main effect by group ($P < .01$).

Figure 5: Time to Low Point of Crouch/Countermovement
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. Note that adults and adolescents spend .1 seconds or longer in countermovement phase based on movement of the trunk. This difference of 100 milliseconds accounted for the significant main effect by group ($P < .01$).

Figure 6: Time of Push-off/Propulsive Phase
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. Note that adults and adolescents spend .1 seconds or longer in countermovement phase based on movement of the trunk. This difference of 100 milliseconds accounted for the significant main effect by group ($P < .01$).

Figure 7: Joint Angles at Low Point/Countermovement Phase
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. Note group 3 (children) have greater flexion angles, indicating deeper amounts of flexion at the bottom of their crouch. Specifically, the hip and knee joints were responsible for significant main effect by group ($P < .01$).

Figure 8: Height Jumped
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. Note that adults and adolescents jump significantly ($P < .01$) higher than children.

Figure 9: Adult Velocity-Displacement Phase Plane
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. The ordinate axis is displacement represented in meters. The X-axis is velocity represented in meters per second. Takeoff is shown on the far right side by the vertical colored lines.

Figure 10: Adolescent Velocity-Displacement Phase Plane
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. The ordinate axis is displacement represented in meters. The X-axis is velocity represented in meters per second. Takeoff is shown on the far right side by the vertical colored lines.

Figure 11: Child Velocity-Displacement Phase Plane
Group 1 represents adults, group 2 represents adolescents, and group 3 represents children. The ordinate axis is displacement represented in meters. The X-axis is velocity represented in meters per second. Takeoff is shown on the far right side by the vertical colored lines. Note the inconsistency in displacement and velocity at the time of takeoff compared to adults and adolescents.

Figure 1. Time to Peak Linear Velocity

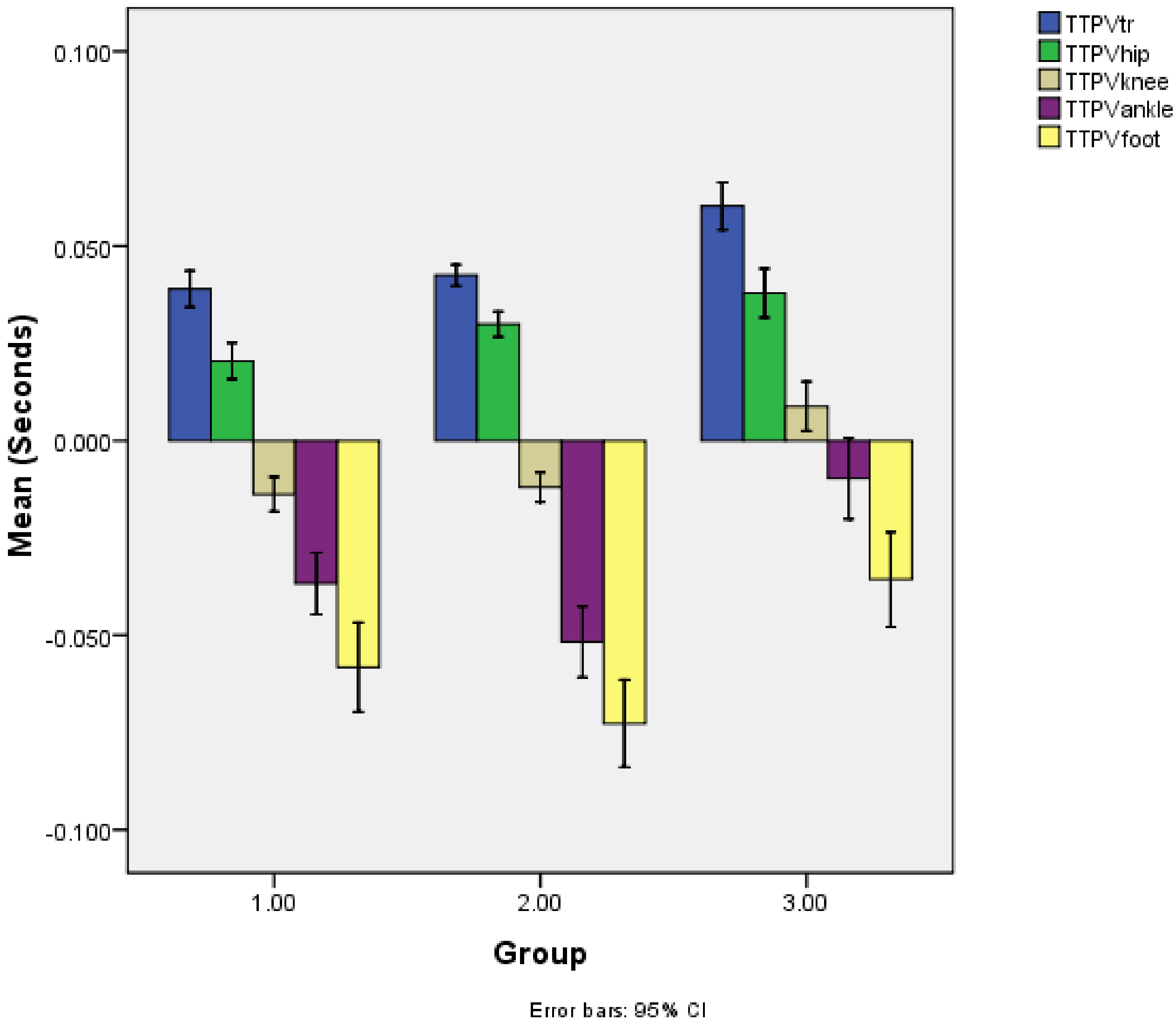

Figure 2. Time to Peak Angular Velocity

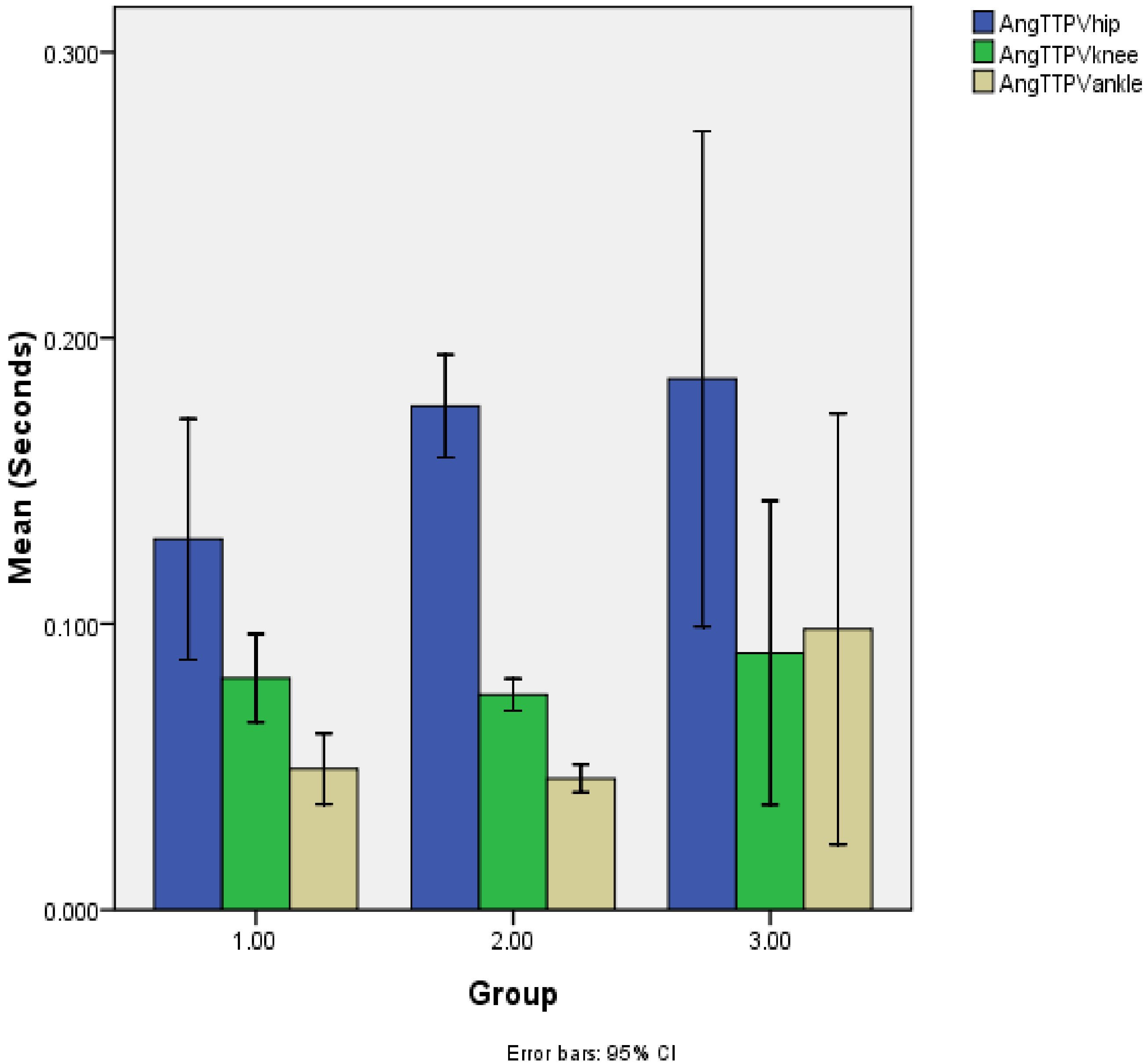

Figure 3. Peak Linear Velocity

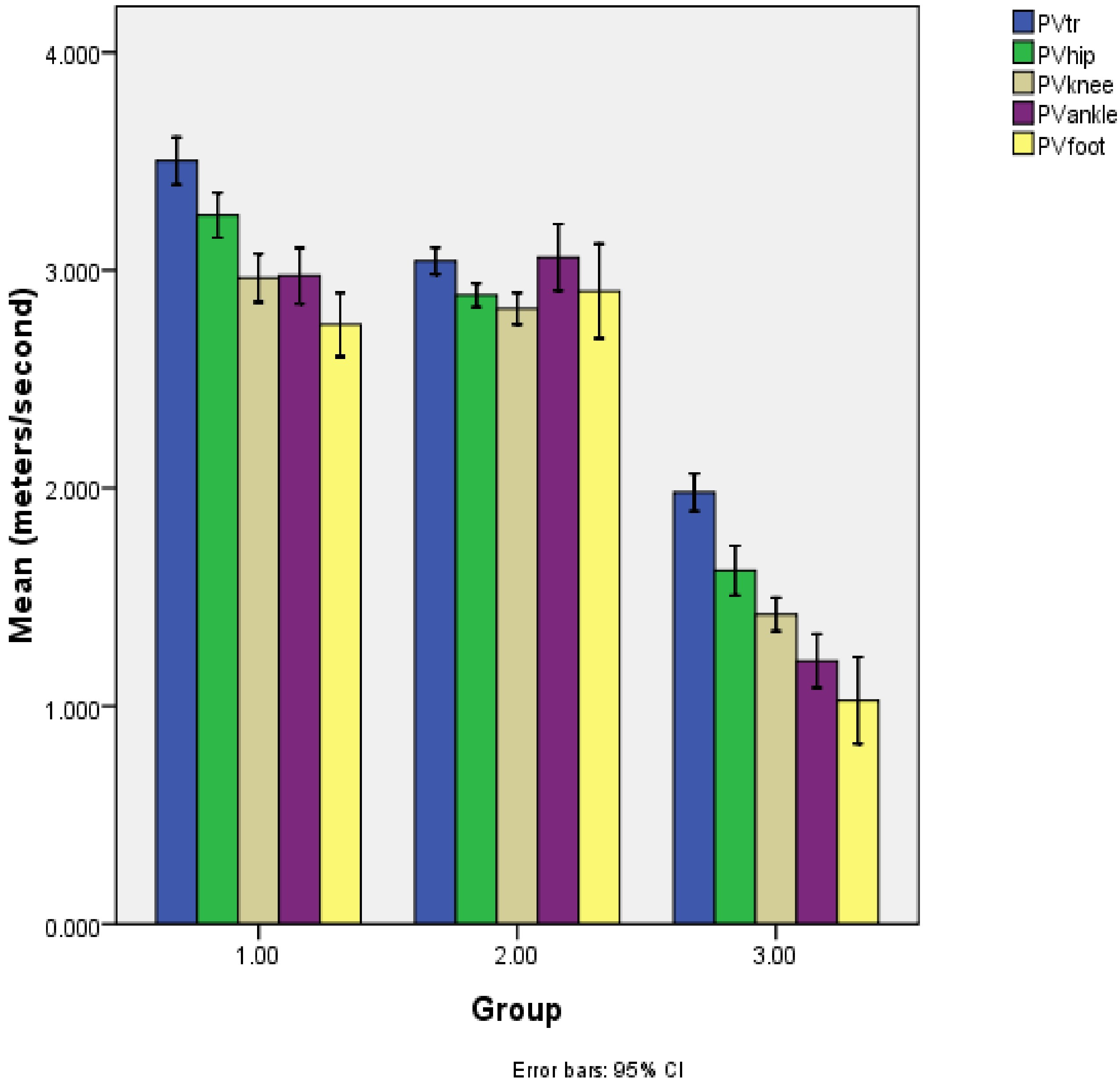

Figure 4. Absolute Timing / Segmental Lag

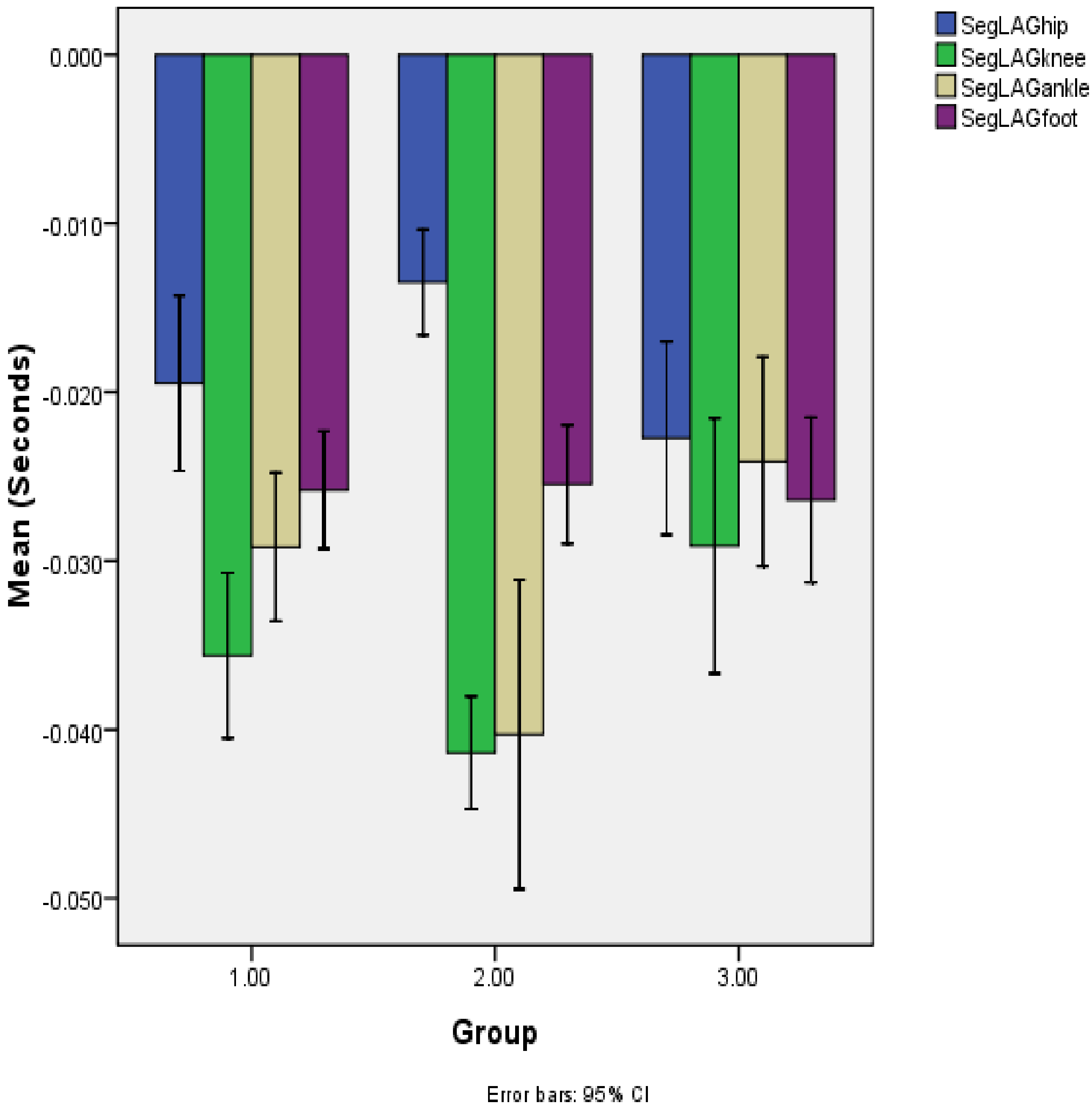

Figure 5. Time to Low Point of Crouch

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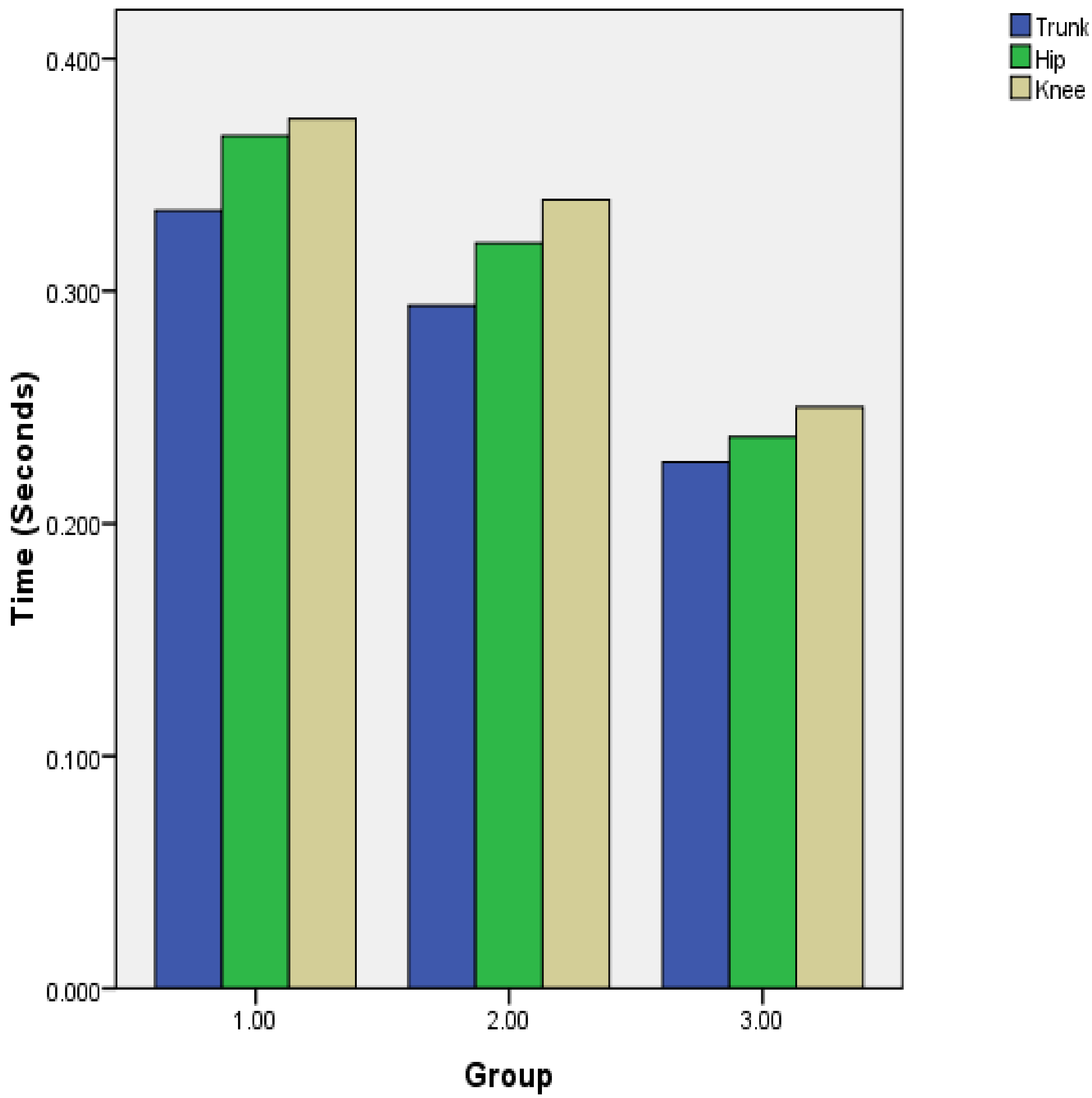


Figure 6. Joint Angle at Low Point/Countermovement Phase

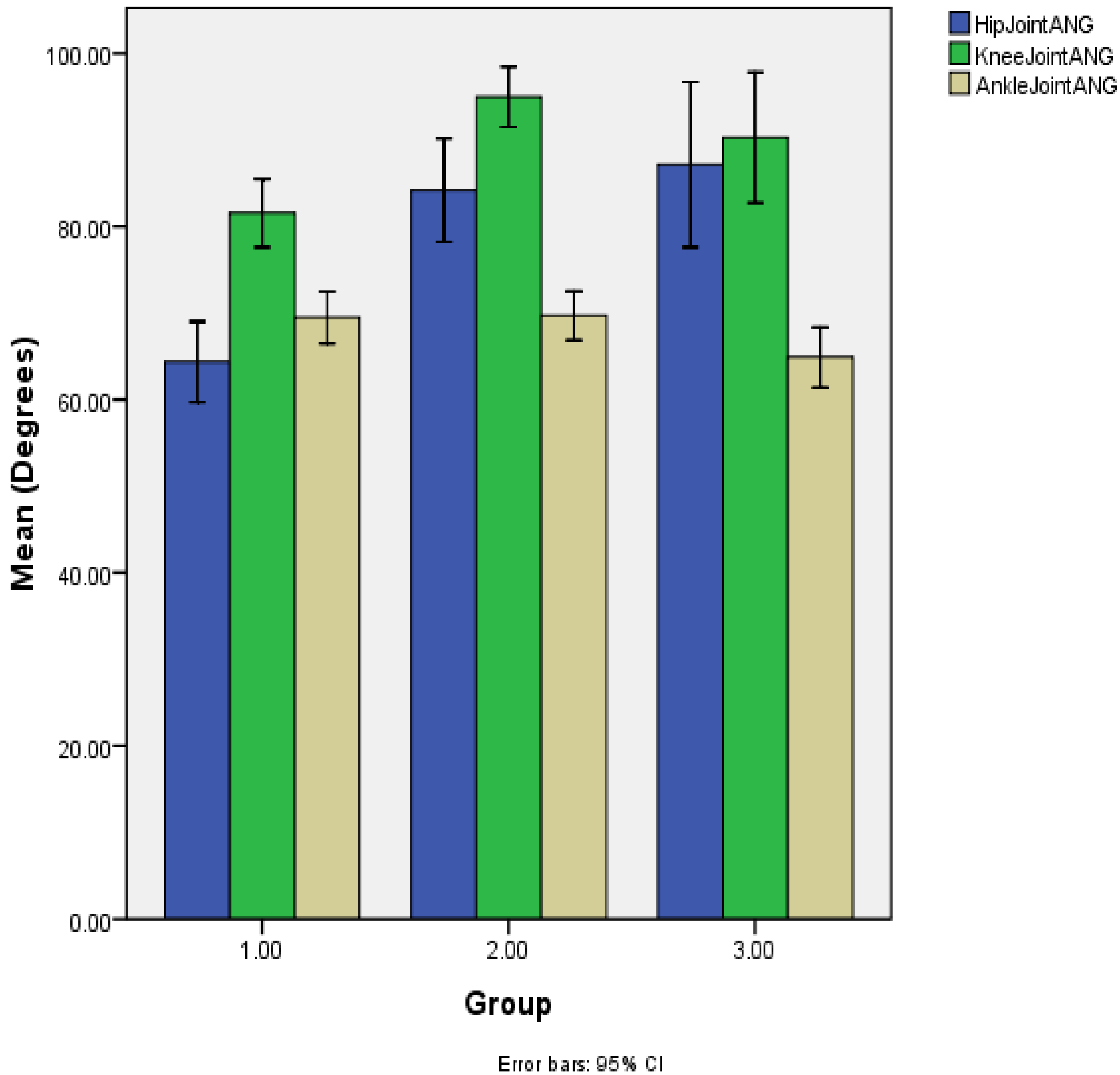


Figure 7. Time of Propulsive Phase

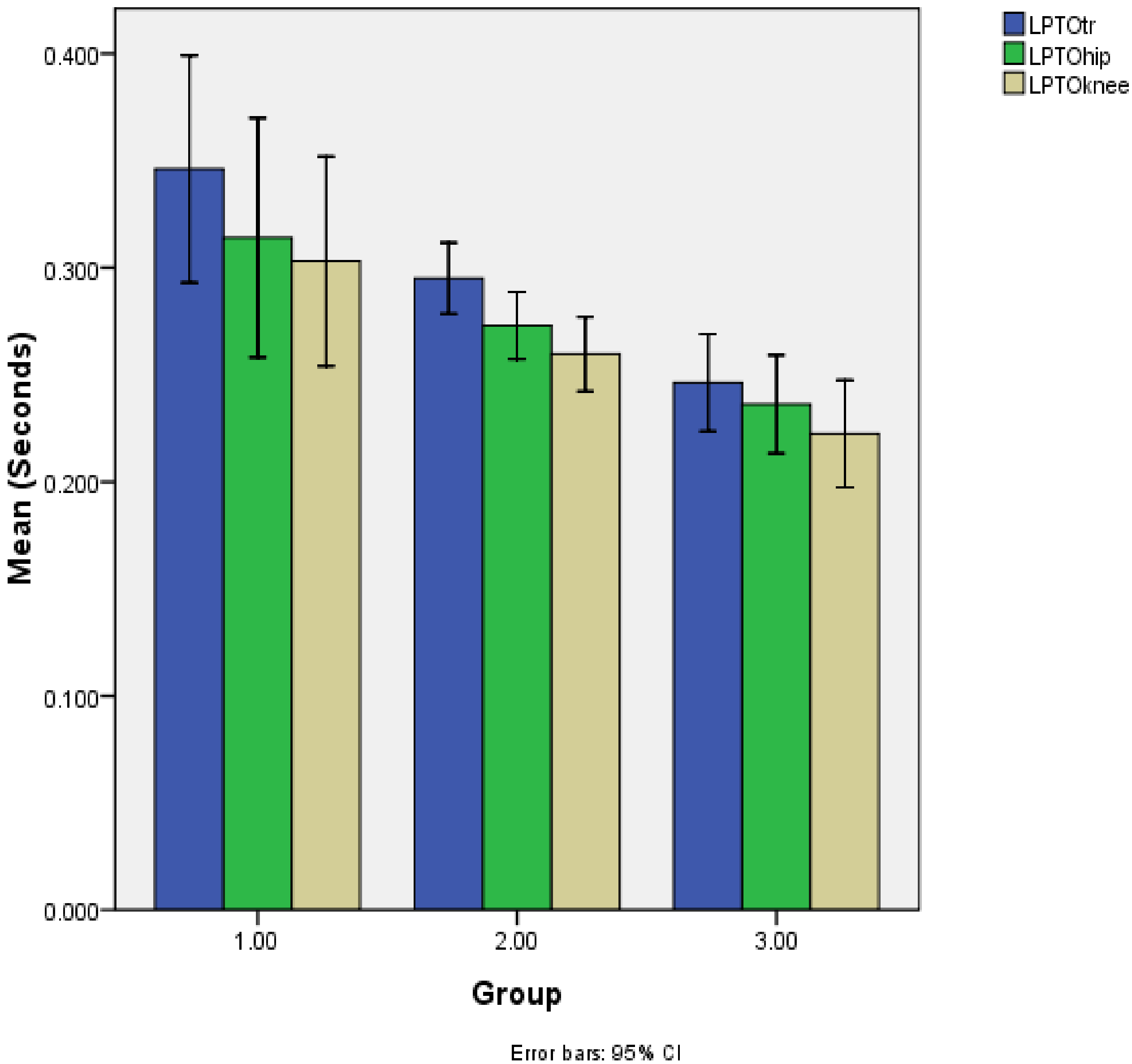


Figure 8. Height Jumped

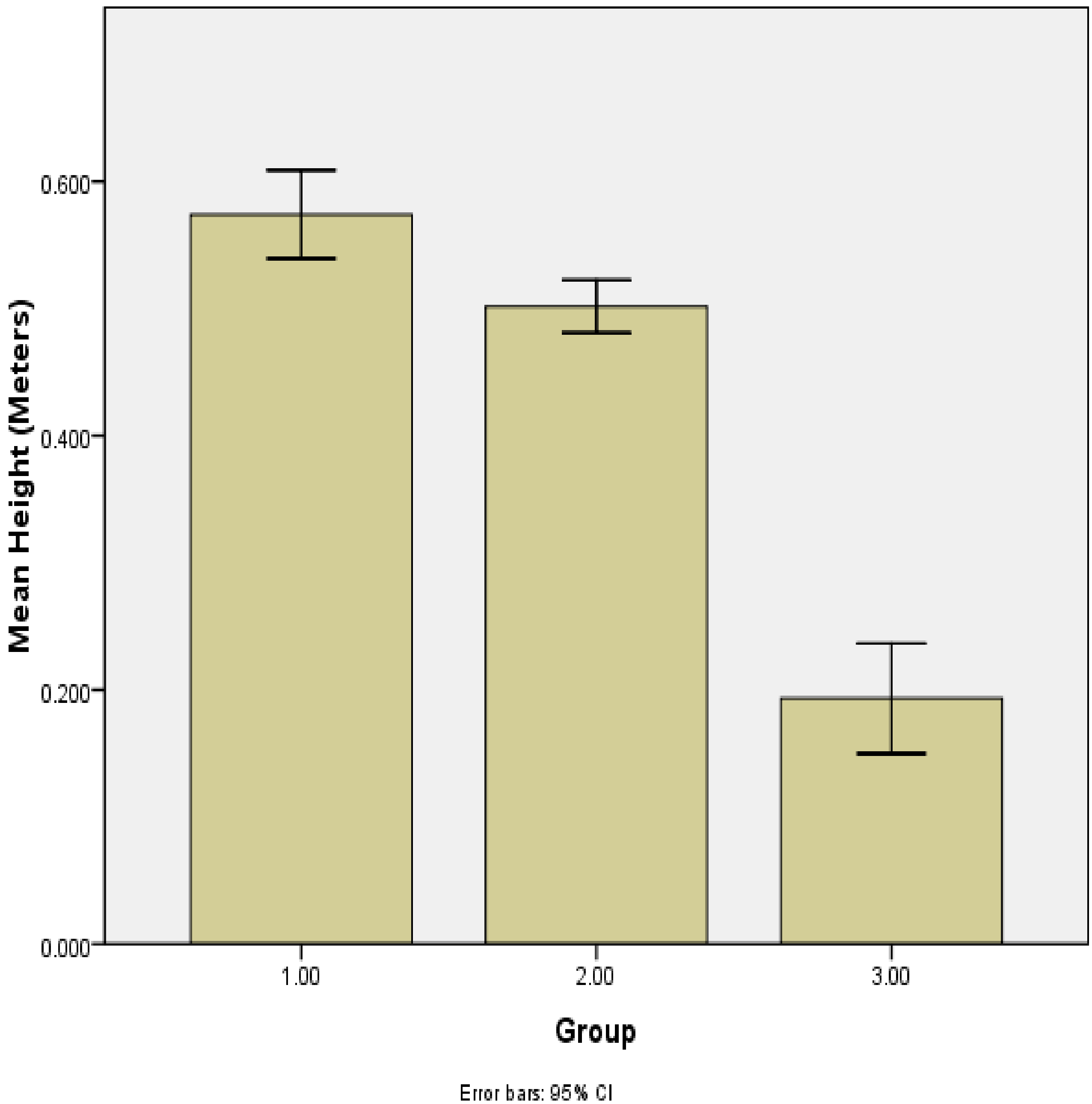


Figure 9. Adult Velocity-Displacement Phase-Plane

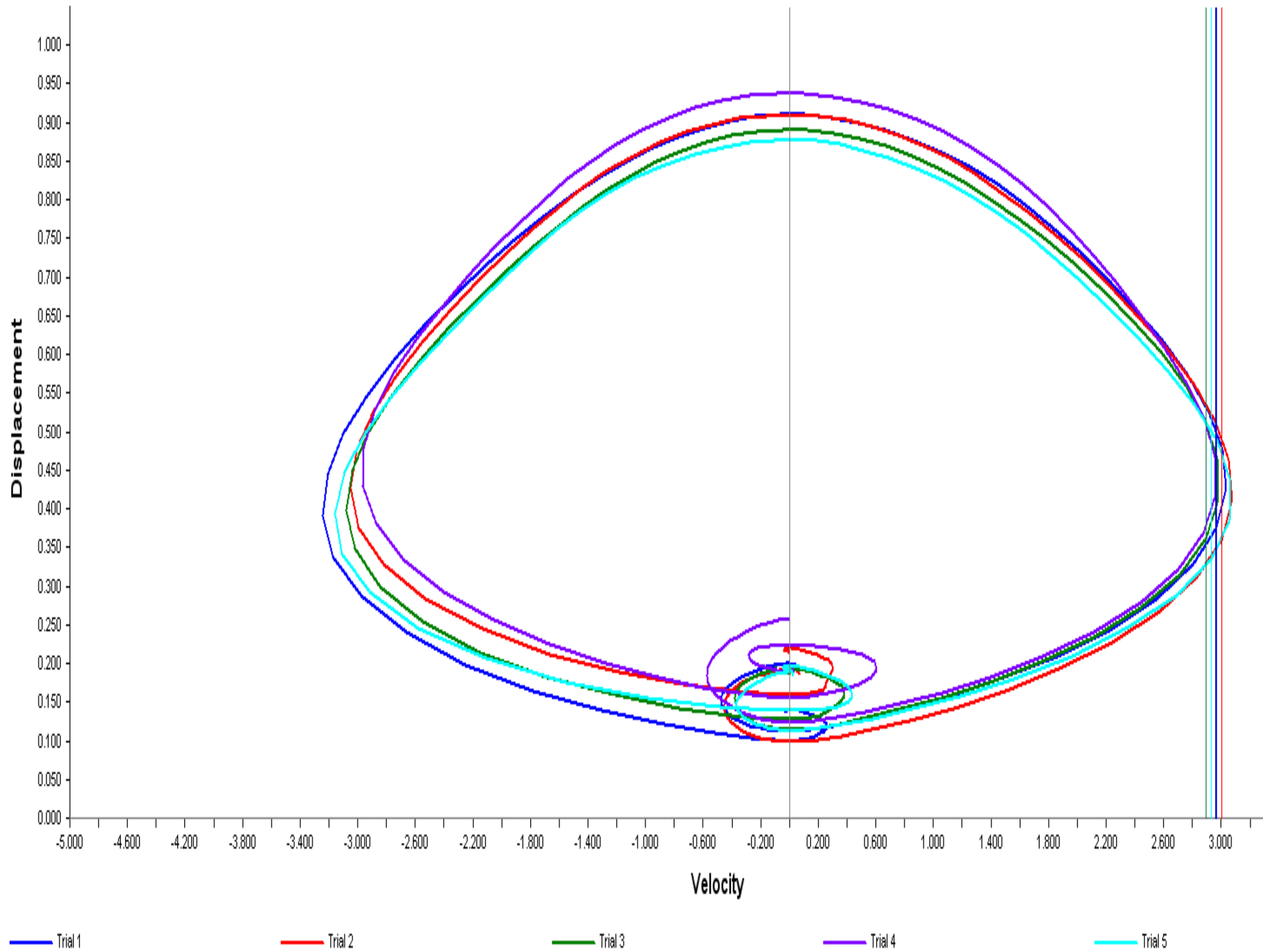


Figure 10. Adolescent Velocity-Displacement Phase-Plane

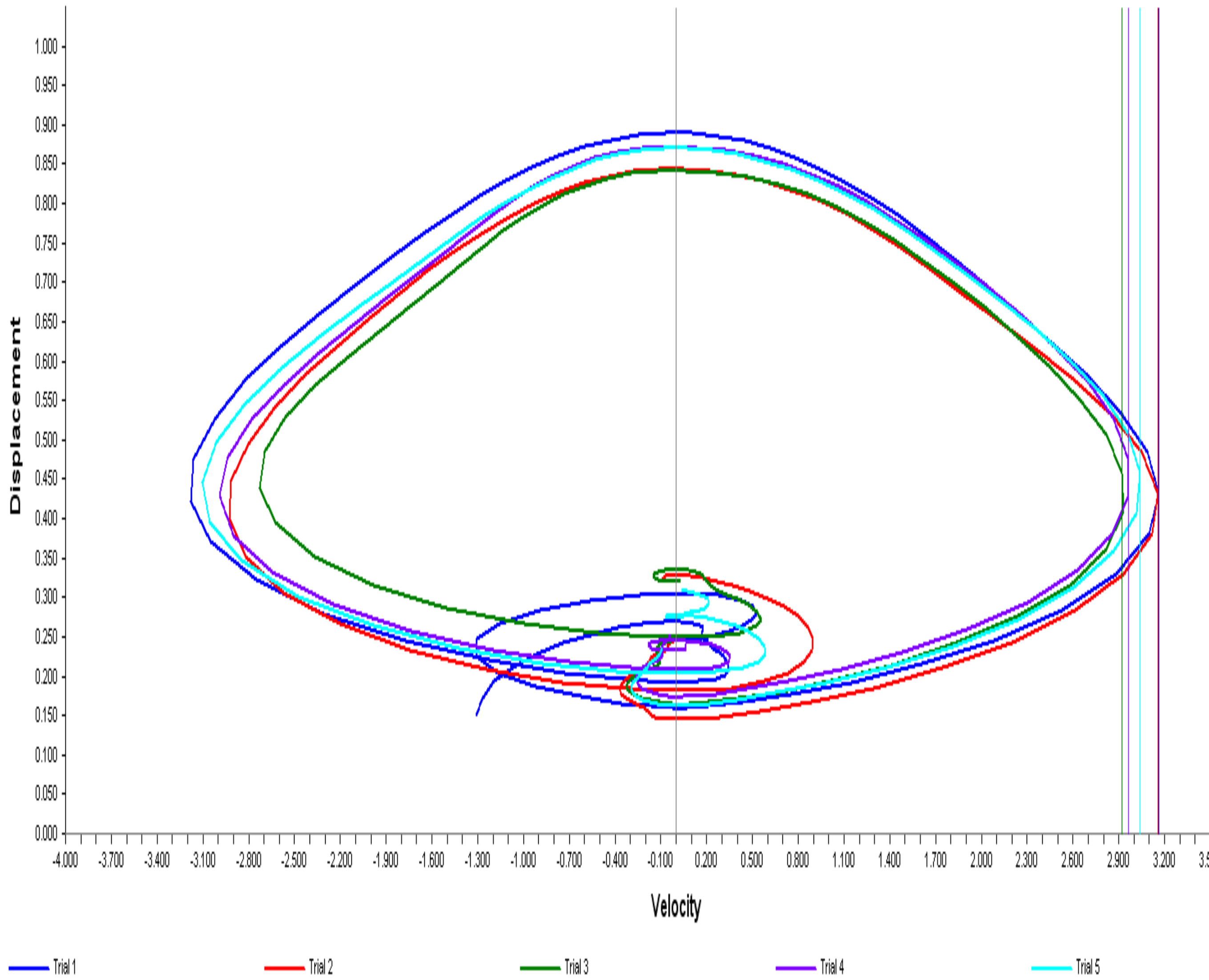
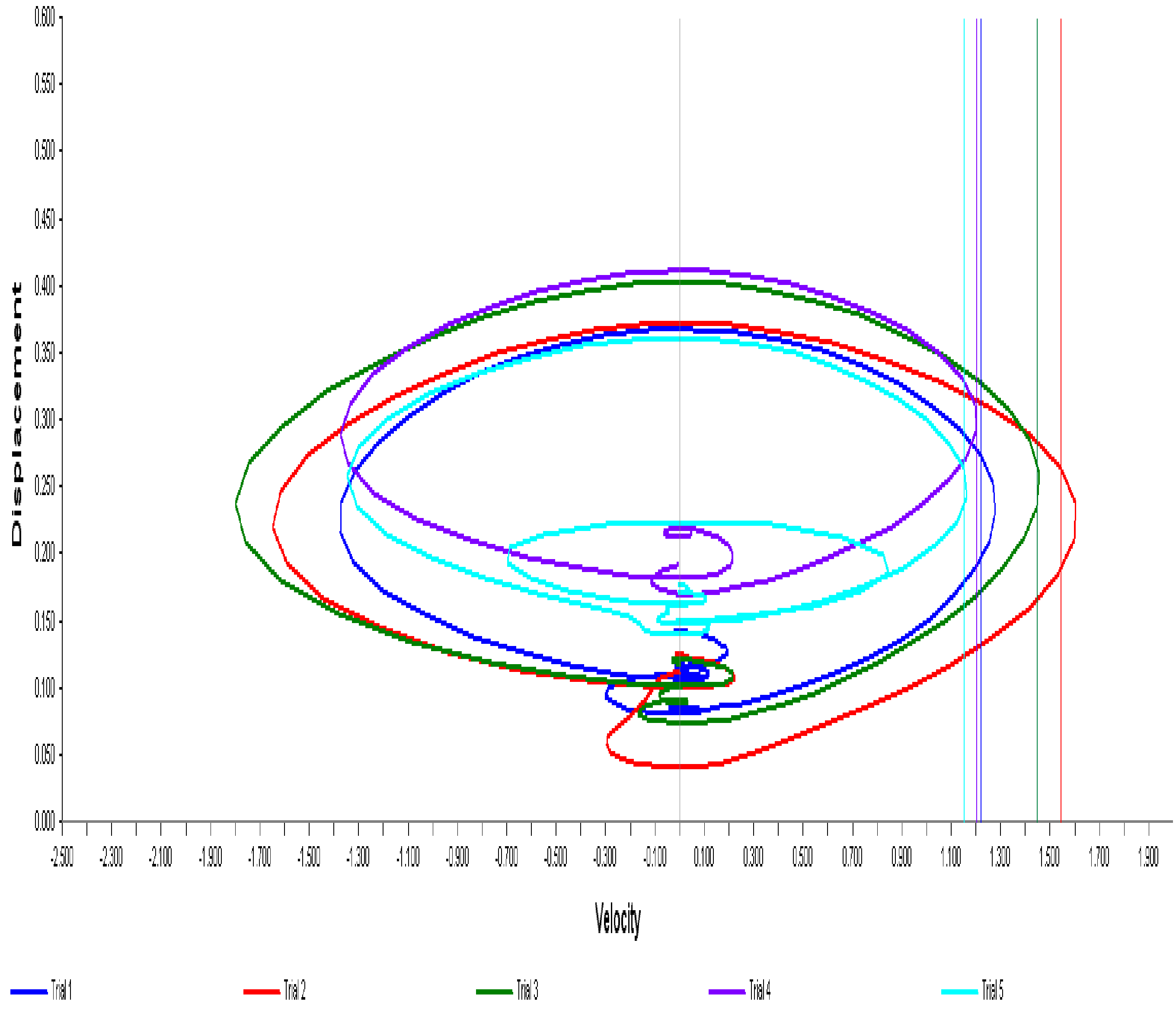


Figure 11. Child Velocity-Displacement Phase-Plane



Appendix A:

Written Summary

This experiment is designed to help determine whether relative and absolute timing of vertical jump changes or remains the same in young children, adolescents, and adults. In addition to providing data that addresses the purpose of the experiment, participants and/or their parents may view their data or their child's data at the completion of the experiment.

Because this study will involve jumping vertically, individuals that have had previous knee and or leg injuries may adversely affect the data collected. Therefore, if you have had previous leg surgery and/or injury, please notify myself or the supervising professor. If you have had previous injuries, your circumstance will be reviewed by the supervising professor and myself to determine if the injuries may adversely affect data collection before you can become a participant.

Should you provide consent, you will have your vertical jump height and jumping pattern recorded. You will be required to perform a warm up of 3 vertical jumps followed by static stretching. Following warm up, you will jump five times attempting to reach maximum vertical height. Your jumps will be recorded on the PEAK Performance system that utilizes two video cameras. Following collection, data concerning the displacement, velocity, and acceleration of your trunk, hip, knee, ankle, and foot will be determined using commercial software. If you feel any pain or discomfort while jumping, let me know and I will discontinue data collection immediately. Participants are free to withdraw their consent and discontinue participation at any time without penalty or prejudice. If you have any questions regarding procedures, I will be happy to address them.

I have discussed the above points with the participant. It is my opinion that the participant understands the risks, benefits, and obligations involved with this project.

____

Investigator

Appendix B:

Consent Form

Project Title:

An Examination of Relative and Absolute Timing in Young Children, Adolescents, and Adult Vertical Jumpers

Investigator: Patrick Greak

I, ___________________________________, hereby certify that I have been told by Patrick Greak of the Department of Kinesiology about research concerning vertical jump and the coordination used to perform the movement in young children, adolescents, and adults. I have been told about the purpose of the project and the procedures to be followed. I understand the possible discomforts, risks, and possible benefits relating to this project.

A written summary of what I have been told is attached. I have been given an adequate opportunity to read the summary.

I understand that I have the right to ask questions about any procedure and to withdraw my consent and participation in the project at any time without prejudice to me.

I hereby freely give consent for my child to take part in this project

____

Signature of Participant

____

Date

If you have any questions at any time concerning this project or your rights as a participant, please call Patrick Greak - Principal Investigator, (936) 336-0400, Dr. Deborah J. Rhea – Chair, Committee for Human Research, Department of Kinesiology, (817) 257-6861.

ABSTRACT

An Examination of Relative and Absolute Timing in Children, Adolescents, and Adult Vertical Jumpers

By Patrick Greak, M.S., 2009
Department of Kinesiology
Texas Christian University
Thesis Advisor: Dr. Dan Southard, Ph.D.

Horizontal Jumping is a well studied fundamental motor skill with established developmental sequences. Surprisingly, comparatively little work has been completed concerning vertical jumping despite its use in many sport and recreational activities. The purpose of this study was to determine age related differences in vertical jump coordination and performance through the examination of kinematic variables. Twenty-eight participants in three different age groups (9 children age 4-6 yrs, 9 adolescents age 12-14 yrs, and 10 adults age 18-25 yrs) performed 5 maximum vertical jumps with countermovement. Three-dimensional data were collected with a Peak Motus Motion Analysis System. Dependent measures were angular displacement of hip, knee, and ankle joint at low point of crouch, time to peak velocity of joints and segments relative to take-off, peak displacement and time to peak displacement of joints and segments relative to take-off, timing between segments and joint angles from crouch to take-off, time from standing to crouch position of counter movement, time from crouch position to take-off, and height jumped. Segmental and joint data were analyzed across age with oneway MANOVA. Time to crouch, time to take off, and height jumped were analyzed with separate oneway ANOVA. Analyses indicated both qualitative and quantitative differences in dependent measures across age groups. Specifically, the knee and ankle joints of adults and adolescents reached peak velocity after take-off, whereas , only the ankle joint of children reached peak velocity after take-off. Also, there was greater height jumped, greater displacement of the hip joint, and greater time to take off with an increase in age. Results are discussed relative to implications for the development of control and coordination for the vertical jump.