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# Role of arm motion in the standing long jump

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**Abstract**

The role of arm motion on the performance of the standing long jump was investigated. Three males performed a series of jumps with free (JFA) and with restricted (JRA) arm motion to determine if arm swing improves jumping distance. The subjects jumped off a force platform and the motion of the body segments were recorded with a four-camera, passive motion-capture system. Jumping performance was defined as the horizontal displacement of the toe between the initial and landing (TD) positions. The subjects jumped 21.2% further on an average with arm movement (2.09 ± 0.03 m) than without (1.72 ± 0.03 m). Seventy-one percent of the increase in performance in JFA was attributable to a 12.7% increase in the take-off (TO) velocity of the center of gravity (CG). Increases in the horizontal displacement of the CG before TO and in the horizontal position of the toe with respect to the CG at TD accounted for the remaining 29% of the improvement in jumping distance. The added balance and control provided by the arms throughout the jumping motion contributed to performance improvement in JFA. The subjects were able to remedy excessive forward rotation about the CG by swinging the arms backwards during the flight phase. Without the freedom to swing the arms during flight, the subjects had to eliminate any excessive forward rotation while still in contact with the ground. This tendency in JRA was manifest in the premature decline in the vertical ground reaction force (VGRF) and the development of a counterproductive backward-rotating moment about the CG just before TO.


*Keywords:* Standing long jump; Arms; Kinematics; Upper body; Stability

## 1. Introduction

Jumping is a fundamental human movement that requires complex motor coordination of both upper and lower body segments. Many previous studies have clarified the role of arm motion in the standing vertical jump (Feltner et al., 1999; Harman et al., 1990; Lees and Barton, 1996; Luhtanen and Komi, 1978; Shetty and Etnyre, 1989). Investigators have also studied various aspects of the standing long jump (Aguado et al., 1997; Horita et al., 1991; Izquierdo et al., 1998), but the role that arms play in this activity remains unclear.

In standing vertical jumps, arm swing improves jump height by increasing the height and the velocity of the body's center of gravity (CG) at take-off (TO) (Feltner et al., 1999; Harman et al., 1990; Luhtanen and Komi, 1978; Shetty and Etnyre, 1989), contributing to the total body vertical momentum (Lees and Barton, 1996), and increasing the peak magnitude of the vertical ground reaction force (VGRF) (Harman et al., 1990; Shetty and Etnyre, 1989). Arm swing may also improve jumping performance by creating an additional downward force on the body when the major hip and knee extensors are in better position to exert VGRF (Feltner et al., 1999; Harman et al., 1990). This downward force slows the contraction velocity of these muscles allowing for greater muscle force development (Hill, 1938). Additional benefits to arm motion such as reduction of the impact force at landing or touch-down (TD) and reduction of the potentially destabilizing horizontal ground reaction force (HGRF) have been reported (Shetty and Etnyre, 1989).

*Abbreviations:* Jumps with free arm motion, JFA; Jumps with restricted arm motion, JRA; Ground reaction force, GRF; Vertical ground reaction force, VGRF; Horizontal ground reaction force, HGRF; Body weight, BW; Center of gravity, CG; Take-off, TO; Landing (touch-down), TD; Least square mean, LSM; Confidence interval, CI

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Previous standing long jump studies have compared the body configurations and joint functions of adults and preschool-age children (Horita et al., 1991), sought significant correlations between jumping performance and a variety of isometric, kinematic, and kinetic parameters (Aguado et al., 1997; Izquierdo et al., 1998), and attempted to relate the control of standing high jumps to the control of standing long jumps (Ridderikhoff et al., 1999). However, researchers have not investigated the role of arm motion in the standing long jump. Maintaining balance in the TO, flight, and TD phases appears to be more challenging in the standing long jump than in the standing vertical jump since the CG does not remain over the lower body throughout the movement. Rotation of the arms during the flight phase of the long jump helps maneuver the body into a position for optimal landing (Herzog, 1986). The present study explores the hypothesis that standing long jump performance is improved when arm movement is employed in the standing long jump.

## 2. Methods

### 2.1. Jumping trials

Three unskilled adult males with (mean $\pm$ standard deviation) height of $1.81 \pm 0.03$ m, mass of $72.3 \pm 13.0$ kg, and age of $29.7 \pm 8.1$ year performed a series of standing long jumps. All subjects were informed of the experimental procedures and gave their consent before participating. Before executing any jumps, the subjects were instructed to warm up for a few minutes by doing some light running, jumping, deep-knee bends, stretching, etc.

For each trial, the subjects were instructed to initially stand on a force platform and jump as far as possible once given a verbal signal. Each subject performed six jumps with free arm movement (JFA) and six jumps with restricted arm movement (JRA). For JRA, the subjects were instructed to hold their hands in front of their abdomen throughout the jump. The subjects executed all jumps without falling at TD.

The impact at TD on the laboratory floor caused noticeable vibrations on the force platform measurements recorded at the TO location. The time of TD was defined as the instant these vibrations occurred. Only the results from 35 of the 36 jumps were included in this study because the first half of one of the jumps was not recorded by the data acquisition system.

### 2.2. Equipment

A three-dimensional (3-D) passive motion-capture system (Qualisys, Inc., East Windsor, CT) was used to measure the kinematics of the body segments during jumping. The motion capture system consisted of four cameras, a force platform, passive reflective markers, and a computer running a software package (Qtrac Capture-Version 2.21, Adaptive Optics Associates, Inc., Cambridge, MA). Each of the four cameras recorded the projection of each marker onto an image plane (120 frames/s). Taking into account the position and orientation of the cameras, the software used direct linear transform (DLT) equations to transform these projections into the 3-D position of each marker in space. The motion-capture data acquisition system was calibrated and configured to allow for the capture of the jumping motion from the initial verbal signal until TD.

The passive reflective markers were attached directly to the skin (and shoe) of each participant to minimize errors between the markers and the actual joint centers (see Fig. 1). The markers were attached at the following locations on the right side of the body: fifth metatarsal head (ball of the foot or toe joint), lateral malleolus (ankle joint), lateral tibial plateau (knee joint), greater trochanter (hip joint), acromonial extremity (shoulder joint), lateral epicondyle of the humerus (elbow joint), and styloid process of the ulna (wrist joint).

### 2.3. Data interpretation using link model

The data from the seven markers were used to develop a two-dimensional (2-D), six-segment (foot, calf, thigh, head/neck/trunk, upper arm, and forearm/hand) link model as shown in Fig. 2. This link model was used to estimate the location of the body's CG throughout each jump. The segmental mass fractions and CG locations were estimated from typical human body characteristics (Gowitzke and Milner, 1988; Hinrichs, 1990). The vector between the origin (location of the toe marker at the initial time) and CG was $r$.

Projectile motion principles were applied to the CG from TO until TD. The components of the CG velocity, $v$, were calculated in both the $x$ and $y$ directions according to

$$v_i(t_{\mathrm{TO}}) = \frac{r_i(t_{\mathrm{TD}}) - r_i(t_{\mathrm{TO}})}{t_{\mathrm{TD}} - t_{\mathrm{TO}}} - \frac{1}{2} a_i (t_{\mathrm{TD}} - t_{\mathrm{TO}}) \quad i = x, y, \tag{1}$$

where $a_i$ are the components of the CG acceleration. Neglecting the air drag force $D$, $a_x = 0$ and $a_y = -g$, where $g$ is the gravitational constant. Including $D$, $a_x = -D_x/m$ and $a_y = \pm D_y/m - g$ where $m$ is the body's mass. The magnitude of $D$ is calculated according to

$$D = \frac{1}{2} C_{\mathrm{d}}\, \rho v^2 A, \tag{2}$$

where $C_{\mathrm{d}}$ is the drag coefficient, $\rho$ is the air density, and $A$ is the area of the body's cross-section perpendicular to the direction of the velocity component. Using reasonable values ($C_{\mathrm{d}} = 1$, $\rho = 1.23\,\mathrm{kg/m^3}$, $v = 3\,\mathrm{m/s}$, and

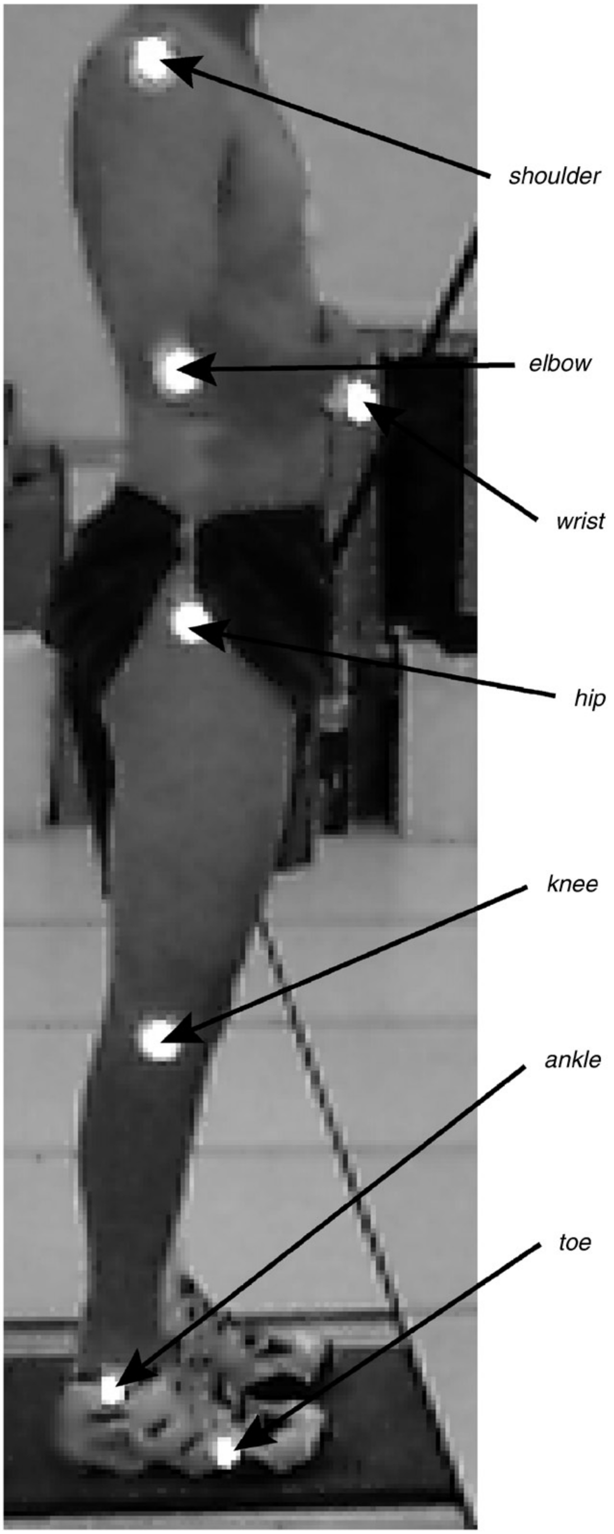


Fig. 1. A subject standing on the force platform with the seven passive reflectors used for motion capture system attached to the skin and shoe at the toe, ankle, knee, hip, shoulder, elbow, and wrist.

$A = 1\,\text{m}^2$) in Eq. (2), the magnitude of the drag force is about 5.5 N. This results in a difference of about 0.02 m/s (<1%) in the components of $v$ at TO. The errors introduced in other parts of this analysis (skin deforma-

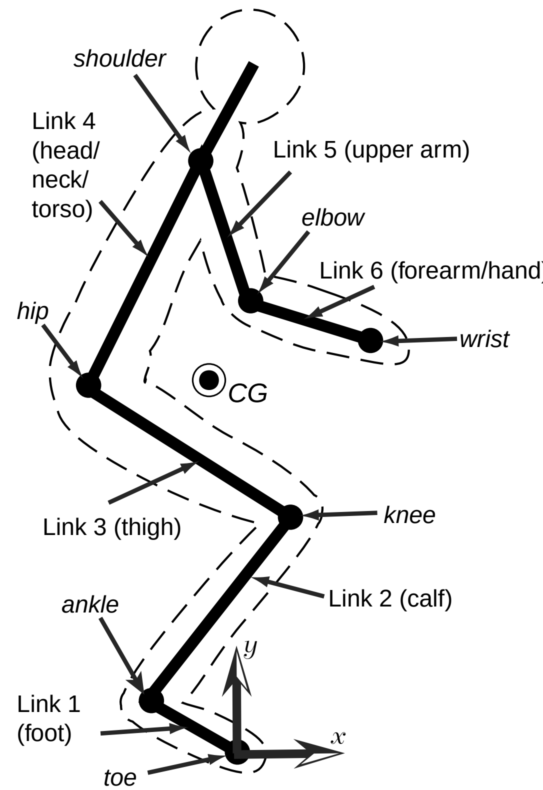


Fig. 2. 2-D, six-segment link model used for data interpretation and for estimation of the location of the body's CG.

tion, segmental mass fractions and CG locations, reduction of 3-D motion to 2-D, reduction of body to six degrees of freedom) are certainly greater than 1%, so the inclusion of the drag force in the calculations for the TO velocity was deemed unnecessary for this study.

### 2.4. Statistics

The statistical software packages SAS System–Enterprise Guide, v.8.1 (SAS Institute, Cary, NC) and R, v.1.3.1 (The R Core Development Team) (Ihaka and Gentleman, 1996) were used to create linear models for each parameter. Each linear model used the parameter value as the dependent variable and subject (1, 2, or 3) and jump type (JFA or JRA) as the independent variables. An interaction term between subject and jump type was included in the model if significant at $p = 0.05$ (only the model for the peak HGRF timing included the interaction term). All assumptions of independence, normality and homogeneity of variances were tested and validated. The results for each parameter were computed for both JFA and JRA and reported as the least square mean (LSM)$\pm$the 95% confidence interval (CI). For each comparison between JFA and JRA, the $p$-value is indicated along with the $R^2$ value for that parameter's linear model.

Table 1
Comparison of key parameters for JFA and JRA (LSM ± 95% CI)

| | JFA | JRA | % Difference |
|---|---|---|---|
| Jump distance (m) | 2.09 ± 0.03 | 1.72 ± 0.03 | 21.2 |
| $r_x$ at TO (m) | 0.57 ± 0.01 | 0.49 ± 0.01 | 16.6 |
| $r$ orientation at TO (°) | 59.7 ± 0.7 | 63.0 ± 0.7 | −5.2 |
| $v$ at TO (m/s) | 3.32 ± 0.03 | 2.95 ± 0.03 | 12.7 |
| $v$ orientation at TO (°) | 38.6 ± 1.1 | 40.2 ± 1.1 | −4.2 |
| $x$-position of toe w/r CG at TD (m) | 0.31 ± 0.01 | 0.29 ± 0.01 | 8.8 |
| Peak VGRF (BW) | 2.31 ± 0.08 | 2.25 ± 0.08 | 2.6 |
| Peak HGRF (BW) | 0.85 ± 0.04 | 0.74 ± 0.04 | 15.4 |
| Peak VGRF time (s before TO) | −0.168 ± 0.034 | −0.217 ± 0.031 | −22.6 |
| Peak HGRF time (s before TO) | −0.085 ± 0.004 | −0.076 ± 0.004 | 12.2 |
| Peak $+M$ (N m) | 173 ± 19 | 134 ± 17 | 29.4 |
| Peak $-M$ (N m) | −115 ± 14 | −87 ± 13 | 32.8 |

Subjects jumped 21% further in JFA than in JRA. This improvement was due to the 16.6% increase in the horizontal displacement of the CG ($r_x$) at TO, the 12.7% increase in the velocity at TO, and in the 8.8% increase in the position of the toe marker with respect to the CG at TD.

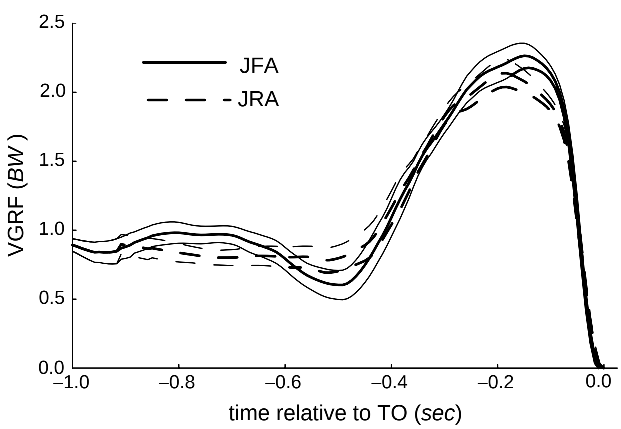


Fig. 3. Profiles of the VGRF for the last 1.0 s before TO for both JFA and JRA (LSM ± 95% CI). Profiles for JFA and JRA were similar until the last 0.2 s before TO, when the profile for JRA trailed off in magnitude earlier than for JFA.

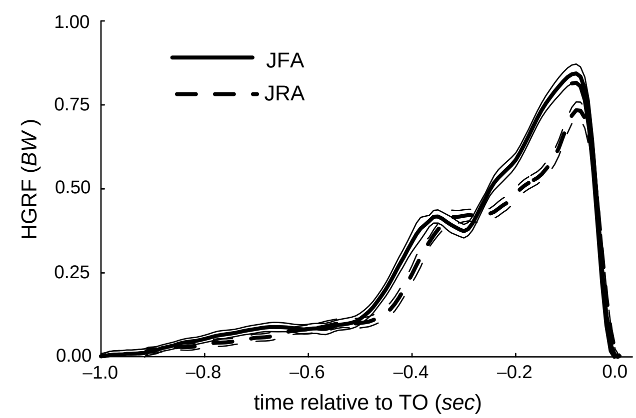


Fig. 4. Profiles of the HGRF for the last 1.0 s before TO for both JFA and JRA (LSM ± 95% CI). HGRF values for JFA were consistently higher over the 0.3 s before TO.

## 3. Results

### 3.1. Jumping distance

The subjects jumped 21.2% further ($p < 0.0001$, $R^2 = 0.930$) with arm movement with average distances of 1.72 ± 0.03 m for JRA and 2.09 ± 0.03 m for JFA (see Table 1 for summary of results). Jumping distance was defined as the horizontal displacement of the toe marker from the initial position to TD location.

### 3.2. CG Kinematics at TO and TD

Arm movement allowed the subjects to increase the horizontal displacement ($p < 0.0001$, $R^2 = 0.763$) of the CG ($r_x$) before TO by 8 cm. The orientation of the vector between the origin and the CG, $r$, was smaller ($p < 0.0001$, $R^2 = 0.765$) for JFA (59.7 ± 0.7°) than JRA (63.0 ± 0.7°).

The average magnitude of the velocity of the CG at TO was 2.95 ± 0.03 m/s for JRA and 3.32 ± 0.03 m/s for JFA, a 12.7% increase ($p < 0.0001$, $R^2 = 0.921$). The TO angle of $v$ was slightly lower ($p = 0.0310$, $R^2 = 0.737$) for JFA (38.6 ± 1.1°) than for JRA (40.2 ± 1.1°).

The distance between the toe and CG at TD was over 2 cm greater ($p = 0.0027$, $R^2 = 0.792$) for JFA (0.31 ± 0.01 m) than for JRA (0.29 ± 0.01 m).

### 3.3. Ground reaction forces

The magnitude of the peak VGRF (see Fig. 3) did not differ significantly ($p = 0.2754$, $R^2 = 0.884$) between JFA (2.31 ± 0.08 BW) and JRA (2.25 ± 0.08 BW). The HGRF peak values (see Fig. 4) for JFA (0.85 ± 0.04 BW) were 15.4% greater ($p = 0.0004$, $R^2 = 0.811$) than for JRA (0.74 ± 0.04 BW).

The peak VGRF occurred 0.168 ± 0.034 s before TO for JFA and 0.217 ± 0.031 before TO for JRA, a 22.6% difference ($p = 0.0386$, $R^2 = 0.571$). The pattern was reversed for the timing of the peak HGRF. The peak HGRF occurred earlier ($p = 0.0050$, $R^2 = 0.854$) for

JFA ($0.085 \pm 0.004$ s before TO) than for JRA ($0.076 \pm 0.004$ s before TO).

Additional qualitative differences were observed in the VGRF profiles for JFA and JRA. Just before TO, the value of the VGRF trailed off earlier for JRA than for JFA. The VGRF magnitude for JFA stayed slightly higher in the range 0.7–0.8 s before TO and dipped considerably lower 0.5 s before TO.

### 3.4. Moment about CG

The general shape of the moment profiles were similar for all subjects (shown for the last 0.25 s before TO in Fig. 5). A positive (counterclockwise) moment ($M$) pitched the subject backward about the CG and a negative moment pitched the subject forward.

All jumps started with a small positive (pitching backward) moment which increased to a maximum near 0.4 s before TO. The peak positive moment was greater ($p = 0.0053$, $R^2 = 0.668$) for JFA ($173 \pm 19$ N m) than for JRA ($134 \pm 17$ N m). From there the moment decreased and became negative (pitching forward) reaching its peak negative magnitude near $-0.15$ s before returning to zero at TO. The peak negative moment magnitude was also greater ($p = 0.0062$, $R^2 = 0.732$) for JFA ($-115 \pm 14$ N m) than for JRA ($-87 \pm 13$ N m). Another qualitative difference between the moment profiles of JFA and JRA was that the JRA moments typically became positive again just before returning to zero at TO.

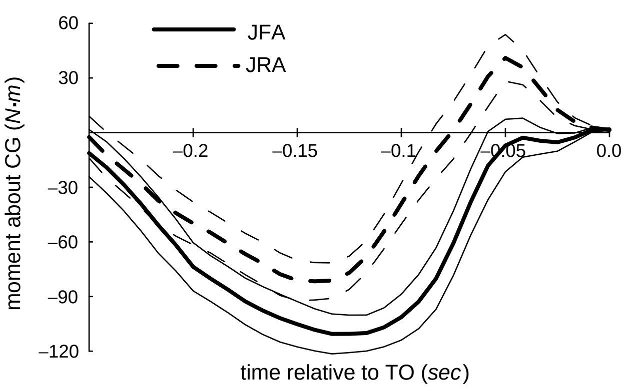


Fig. 5. Moment profiles of the GRF about the CG for the last 0.25 s before TO for both JFA and JRA (LSM ± 95% CI). Subjects generated greater positive (pitching backward) and negative (pitching forward) magnitudes of the moment about the CG for JFA. A counter-productive backward-pitching moment is generated over the last 0.075 s before TO for JRA.

## 4. Discussion

In this study, the hypothesis that swinging the arms improves jumping performance was explored. The subjects in this study jumped over 36 cm (21.2%) further with arm motion than without. On average, 71% (26 cm) of the improvement was due to the increased CG displacement in the flight phase caused by the greater TO velocity, 22% (8 cm) of the improvement was due to the increase in the horizontal displacement of the CG before TO, and the remaining 7% ( > 2 cm) was due to the increase in the distance between the toes and CG at TD.

Results for JFA for the present study are comparable with findings from previous standing long jump investigations (see Table 2). The jumping distances and TO velocity in the present study are less than in previous studies. This could be due to the differences in athletic ability of the subjects since previous studies used collegiate volleyball players (Horita et al., 1991) and students studying physical education (Aguado et al., 1997; Izquierdo et al., 1998). The value for the orientation of $v$ at TO for the present study of 38.6° was very close to the 37.5° found by Aguado et al. (1997). The peak VGRF values agree very well with previous studies (2.2–2.3 BW). The peak HGRF values show more variation with the value for the current study (0.85 BW) falling between the low (0.63 BW) and high (1.29 BW) values previously reported.

No previous studies have explored the role of the arms in the standing long jump, so the arm contributions to the standing long jump must be compared to

Table 2
Comparison of jump length, velocity at TO, and GRF results for JFA from previous standing long jump studies performed by Aguado et al. (1997), Horita et al. (1991), and Izquierdo et al. (1998)

| | Present study | Aguado | Horita | Izquierdo |
|---|---|---|---|---|
| Jump length (m) | 2.09 | n/a | 2.75 | 2.53 |
| $v$ at TO (m/s) | 3.32 | 4.04 | 3.74 | 3.5 |
| $v$ orientation at TO (°) | 38.3° | 37.5° | 29.2° | n/a |
| Peak VGRF (BW) | 2.31 | 2.27 | 2.16 | 2.3 |
| Peak HGRF (BW) | 0.85 | 0.63 | 1.29 | n/a |

The value for $v$ orientation at TO for Horita et al. was calculated from the reported data. The value for the same parameter reported by Aguado et al. (1997) is 25°. However, this is inconsistent with the values they reported for the horizontal and vertical components of the CG velocity at TO. The value presented here is consistent with these velocity components.

similar standing vertical jump investigations. The present study found an increase of 8 cm in the horizontal displacement of the CG before TO when arm motion was allowed. Comparable vertical jump studies report pre-TO increases of 4.5 cm (Harman et al., 1990) and 6.1 cm (Feltner et al., 1999) in the vertical displacement of the CG. The increase in the TO velocity due to arm motion in standing long jumps was found to be 12.7%, which is similar to the values reported for standing vertical jumps of 10% (Harman et al., 1990; Feltner et al., 1999) and 12.7% (Luhtanen and Komi, 1978).

The majority (71%) of the improvement in standing long jump performance with arms is due to the increase in the CG velocity at TO. The precise mechanisms by which arm swing caused the CG to achieve greater TO velocity are still unclear. The additional momentum imparted to the system by the swinging of the arms may contribute to the increase in the TO velocity. Another factor is that the lower body extensor muscles may be exerting more force in JFA. Past researchers of vertical jumping have proposed that arm swing enhances the force producing capabilities of the lower extremity extensor muscles by slowing the contraction velocity at key times in the movement (Harman et al., 1990; Feltner et al., 1999). In addition, slight differences in the lower body joint angles between JFA and JRA cause changes in the lengths of the lower body extensor muscles, which could result in more efficient force production (Hill, 1938). These mechanisms for force enhancement also may be present in standing long jumps. In addition to these possible explanations, the results from the present study point to another explanation for the improvement in the TO velocity in JFA.

Some of the performance improvement with arms was due to the added balance and control the arms provided to the total movement. During any human body activity, arm movements can be used to regain or maintain balance through the transfer of angular momentum to the arms from the rest of the body. To maintain balance throughout the jump, the subjects may have "held back" or even employed counterproductive mechanisms that reduced jumping distance in JRA.

The VGRF profiles suggest that the jumpers may hold back during the TO phase of JRA. The magnitude of the VGRF trailed off sooner before TO in JRA than in JFA for all three subjects (see Fig. 3). Also, the peak value of the VGRF occurred 0.049 s earlier in JRA. This indicates that the subjects may not have used all available muscle force near the end of the TO phase in JRA so that they could maintain stability throughout the jump until TD. Once a jumper is in the air, he cannot change the body's total linear or angular momentum before TD. When arm movement is allowed, excessive forward rotation about the body's CG can be alleviated by swinging the arms back in the flight phase. If this capability is removed as in JRA, the subject must restrict the forward pitching of the body while still in contact with the ground.

The moment profiles (see Fig. 5) also support the idea that the subject is constrained by the need to maintain stability throughout the jump. The GRF provided a positive (pitching backwards) moment up until approximately 0.25 s before TO. At this point the moment became negative, pitching the body forward in preparation for TO. This negative moment reached a minimum and then returned back to zero at TO for JFA. However, in JRA the moment became considerably positive before returning to zero at TO. A positive moment of the GRF just before TO is counterproductive to the objective of propelling the body forward in the horizontal direction. However, this late positive moment served the same purpose in JRA as the swinging of the arms in the flight phase did in JFA. These mechanisms were necessary to avoid excessive forward rotation of the body during the flight and landing phases of the jumping movement.

The stability of a system's configuration decreases as the horizontal distance between the body's CG and the point of ground support increases. The remaining 29% of the increased jumping distance in JFA was attributable to the greater horizontal distance between the CG and the toes at TO and TD. The ability of the arms to maintain or recover balance allowed the jumpers to use less stable body configurations for an improvement of almost 11 cm.

The differences between the extreme values of the GRF moments for JFA and JRA also support the concept that arm swing allows the jumper to employ less stable configurations. Large moments are destabilizing by nature since they accelerate the body's rotation about the CG. The peak positive and negative moments were 29% and 33% greater in JFA than in JRA. This indicates the jumpers may have held back in JRA, avoiding large moments that they may not have been able to effectively control without the extra freedom and control provided by arm swing.

Future investigations could provide further insight into the motor control principles of activities involving both upper and lower body motion. Angular momentum analyses would be helpful in quantifying the effects arm swing has upon the balance and control throughout the standing long jump movement. Segmental linear momentum analyses could determine how much of the performance improvement is due to the additional momentum the arm swing imparts to the system. Joint moment studies could verify whether or not the lower body extensor muscles are generating more force in JFA than in JRA. However, in order to determine the cause of the extra force generation, these studies would need to be combined with forward dynamic simulations that include accurate representations of musculotendon actuators. These simulations could help determine if arm swing changes the lengths or slows the contraction of the lower-body extensor muscles and therefore enhances force generating capacity and/or if less force is generated in JRA because the jumper holds back to maintain balance and control in the standing long jump movement.

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