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Effect of arm motion on standing lateral jumps

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ABSTRACT

The role of arm swing in jumping has been examined in numerous studies of standing jumps for height and forward distance, but no prior studies have explored its effect on lateral jumping. The purpose of the present study was to investigate the effect of arm motion on standing lateral jump performance and to examine the biomechanical mechanisms that may explain differences in jump distance. Six participants executed a series of jumps for maximum lateral distance from two in-ground force platforms for two jump cases (free and restricted arms) while an eight-camera, passive-reflector, motion capture system collected 3D position data throughout the movements. Inverse kinematics and dynamics analyses were performed for all jumps using three-dimensional (3D) link models to calculate segment angular velocities, joint moments, joint powers, and joint work. Free arm motion improved standing lateral jump performance by 29% on average. This improvement was due to increased takeoff velocity and improved lateral and vertical positions of the center of gravity (CG) at takeoff and touchdown. Improved velocity and position of the CG at takeoff resulted from a 33% increase in the work done by the body. This increase in work in free arm jumps compared to restricted arm jumps was found in both upper and lower body joints with the largest improvements (>30 J) occurring at the lower back, right hip, and right shoulder.

1. Introduction

Explosive movements, such as jumping in multiple directions, are frequently encountered in many sports like basketball, volleyball, tennis, baseball, American football, soccer, and rugby. Jumping demands complex coordination of all segments of the body to achieve maximum performance. In numerous sporting events, the motion of upper extremity segments can be constrained while carrying a ball or a racket or even while navigating tight spaces in between or around other competitors. The contributions of upper body extremity movement to performance have been demonstrated in numerous standing vertical jump studies (Feltner et al., 1999; Harman et al., 1990; Lees and Barton, 1996; Luhtanen and Komi, 1978; Shetty and Etnyre, 1989). Researchers have also investigated standing forward jumps to document the benefits of jumping with arms and to describe the mechanisms underlying performance improvement (Ashby and Delp, 2006; Ashby and Heegaard, 2002; Hara et al., 2008; Wu et al., 2003). Despite the presence of lateral jumping maneuvers with free and with constrained arm motion in numerous sporting events, no prior research has explored the role of arms in sideways jumping. Greater understanding of how arm motion affects lateral movements could help in developing training strategies to maximize performance or to minimize injuries.

Several mechanisms have been proposed to explain improved performance due to arm movement in jumping. The “impart energy” theory describes the phenomenon of upper extremity muscles doing work at the shoulder and elbow joints, which provides mechanical energy that is transferred to the rest of the body (Ashby and Delp, 2006). This added energy has been demonstrated to be the greatest contributor to enhanced performance in vertical (Lees et al., 2004) and forward (Ashby and Delp, 2006) jumps by serving to increase the velocity and vertical position of the center of gravity (CG) at takeoff (Ashby and Heegaard, 2002; Feltner et al., 1999; Harman et al., 1990; Luhtanen and Komi, 1978; Shetty and Etnyre, 1989).

The “joint torque augmentation” theory attempts to explain why swinging the arms results in greater lower extremity work as well. The idea behind this theory is that swinging the arms causes a downward force at the shoulder, which slows lower body joint extension velocities, thus decreasing muscle-shortening velocities and enabling muscles to generate more force consistent with the force-velocity properties of muscle (Feltner et al., 1999;

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Harman et al., 1990). Lees et al. (2004) found greater joint torque in combination with lower joint angular velocities in vertical jumps, but they rejected this theory because the combination of greater torque with lower angular velocities did not result in greater power or work generation. A standing long jump simulation study, however, supported the joint torque augmentation theory by finding increased joint torque, power, and work at the hip and ankle due to arm movement slowing joint extension velocities (Ashby and Delp, 2006). Vertical jump simulations developed by Cheng et al. (2008) and Domire and Challis (2010) also demonstrated torque augmentation at the hips due to arm motion.

The "hold back" theory, first proposed by Ashby and Heegaard (2002) as a mechanism for enhanced performance due to arm motion in standing forward jumps, suggests that without the ability to rotate the arms backwards during flight to help position the body for landing, jumpers need to "hold back" or limit the activation of lower-extremity extensor muscles during the propulsive phase of the jump. An optimal control simulation study of the standing long jump found evidence of "holding back" during the propulsive phase of restricted arm jumps (Ashby and Delp, 2006). Restricted arm jumps demonstrated reduced activation levels before takeoff at the hip, knee, and ankle, which resulted in lower joint torques, powers, and work.

Numerous studies have provided insight into the effect of arm motion on vertical and forward jumping performance, but the effect of arm motion on lateral jumping has not been studied. The purposes of the present study were to test the hypotheses that (1) arm movement increases standing lateral jump distance and that (2) any improvement can be explained by impart energy and joint torque augmentation theories.

2. Methods

2.1. Experimental design

Six physically active adult males (age: 26.7 ± 2.4 years, mass: 85.5 ± 10.6 kg, height: 1.823 ± 0.097 m, mean ± standard deviation) without any persisting musculoskeletal injuries and limitations placed on their physical activity by a medical professional, volunteered and provided informed consent to participate in this study. The protocol for this study was approved by the Human Research Review Committee at Grand Valley State University. Passive reflective markers were secured with double-sided tape to the skin and clothing of each participant using a marker set previously described in Hickox et al. (2016). The participants warmed up by jogging at a self-selected comfortable speed for 5 min on a treadmill and then were allowed to stretch, if desired. Participants practiced each type of jump three to four times prior to data acquisition to familiarize themselves with the jumping motions.

For all trials, three-dimensional positions of the reflective markers were captured at 120 Hz by eight MX-T40 Vicon cameras using Vicon Nexus software (v2.5) (Vicon Motion System Ltd, Los Angeles, CA, USA). Ground reaction forces, free moments, and center of pressure locations for both feet were recorded at 1200 Hz with two in-ground AMTI force plates (Advanced Mechanical Technology Inc., Watertown, MA, USA). Static trials were conducted with each participant standing on the force plates to collect data used for determining segmental parameters and joint center locations. The participants completed additional trials in which they performed flexion/extension, abduction/adduction, and circumduction movements with each shoulder and hip to facilitate joint center determination using the SCoRE method (Ehrig et al., 2006). Each participant then executed two types of lateral jumps to the right: (1) with free arms and (2) with arms restricted by placing and holding both hands on the hips (Fig. 1). For each jumping trial, the participants were directed to stand with one foot on each force plate and then jump as far as possible to the right once given a verbal signal. They were instructed to take off and land with both feet at approximately the same time. All participants performed each type of jump six times alternating between the two jump types. They were allowed time to rest between jumps, if desired.

2.2. Data analysis

The marker position data for all trials were labeled and gaps were filled using spline, pattern, or rigid body algorithms with Vicon Nexus software (v2.5). Only the results from 68 of the 72 jumps were included in the analysis for this study due to data acquisition issues for four jumps (two with free arms and two with restricted arms for which gaps were not able to be filled) for one subject. After exporting the data from Nexus, the remaining data processing and analysis were completed using custom code written in MATLAB R2017a (MathWorks, Natick, MA, USA). The marker position and force plate data for each jump were extracted and filtered using a 4th-order, dual pass, zero-lag Butterworth filter with a cutoff frequency of 10 Hz.

A 3-D link model previously described by Hickox et al. (2016) with 12 segments (feet, shanks, thighs, pelvis, head-neck-trunk, upper arms, and forearms-hands) and 11 joints (ankles, knees, hips, lower back, shoulders, and elbows) was used. The end of the takeoff phase was defined as the time when the vertical ground reaction force dropped below 20 N for the right force plate. The start of the takeoff phase was defined to be 1.2 s before takeoff because at this time no significant movement had yet begun for any of the jumps. Inverse dynamics techniques were employed to calculate the components of the net moments and intersegmental forces during the takeoff phase of the jump at all 11 joints, resulting in 66 scalar unknown variables. The Newton-Euler equations of motion were derived for all 12 segments, resulting in 72 scalar equations. The over-determinacy that resulted from having six more equations than unknown variables was resolved by discarding the six equations derived from the head-neck-trunk segment. This allowed for the moments and forces for the ankles, knees, hips, and lower back to be determined using a "bottom-up" solution method from the ground up to the lower back while the moments and forces for the elbows and shoulders were determined using a "top-down" solution method from the hands "down" to the shoulders as described by Vlietstra (2014) and Ashby et al. (2015).

The net power at each joint (P_j) throughout the takeoff phase of the jumps was calculated consistent with the following equation:

$$P_j = \boldsymbol{M}_j \cdot \boldsymbol{\omega}_j = M_{j_x}\omega_x + M_{j_y}\omega_y + M_{j_z}\omega_z \quad (1)$$

where $\boldsymbol{M}_j$ is the net joint moment and $\boldsymbol{\omega}_j$ is the joint angular velocity, both expressed in the anatomical reference frame of the segment distal to the joint. Power is a scalar so it cannot rightly be broken in components. Nevertheless, as illustrated in Eq. (1), power can be calculated as the sum of three scalars. These three scalars can be thought of as the power due to the moments about the x, y, and z axes, respectively.

The net work at each joint was calculated by numerically integrating the joint power over the 1.2 s of the takeoff phase for each jump. Total body work was obtained by summing the joint work for all 11 joints.

Jump distance was defined as the lateral distance between the right foot (specifically, the right 5th metatarsal head marker) at takeoff and the left foot (specifically, the left 5th metatarsal head marker) at touchdown.

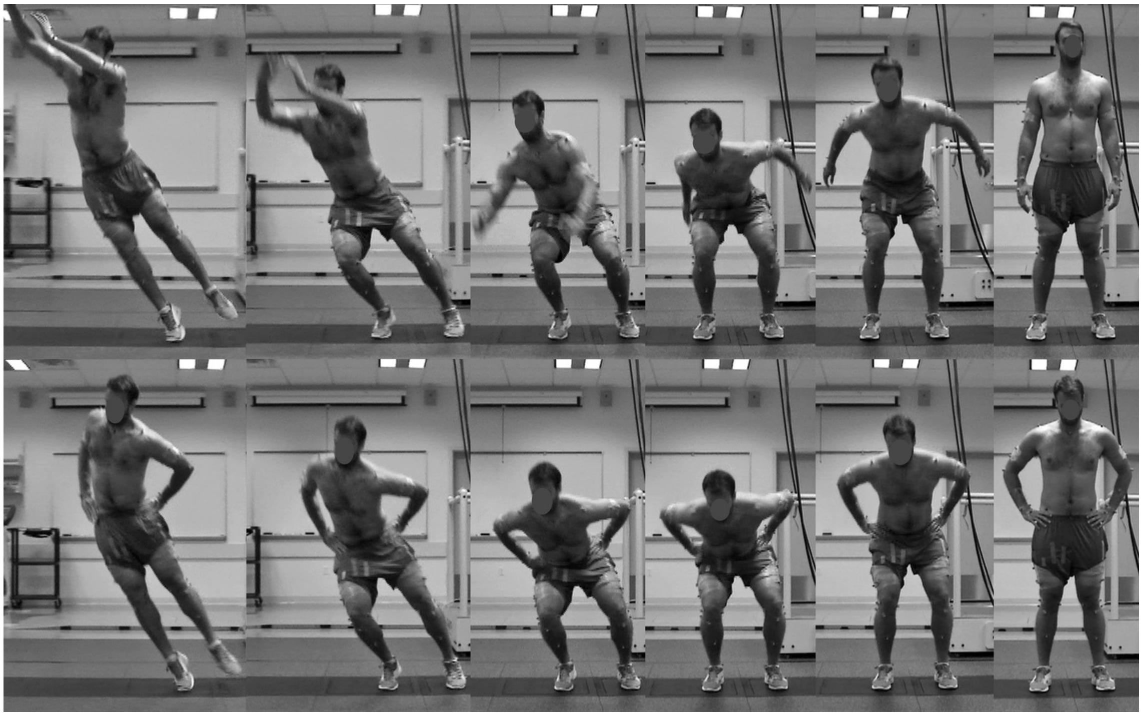

Fig. 1. Screenshots of takeoff phase of standing lateral jumps for free (top) and restricted (bottom) arm jumps.

The total body CG positions for each jump were calculated using the weighted averages of the CG positions of each segment of the link model. CG velocities were calculated by numerically differentiating the CG positions. Neglecting the effects of air drag, projectile motion formulas show the distance (x) traveled by the CG during flight depends on the CG takeoff velocity magnitude (v_{to}) and angle (θ_{to}) and the CG height at takeoff (z_{to}) and touchdown (z_{td}):

$$x = \frac{v_{to}\cos(\theta_{to})}{g}\left(v_{to}\sin(\theta_{to}) + \sqrt{v_{to}^2\sin^2(\theta_{to}) - 2g(z_{td} - z_{to})}\right) \quad (2)$$

Eq. (2) was used to estimate the relative contributions to increased jump distance as a result of improvements in each of these parameters in jumps with free arm motion. A more thorough explanation of how this equation was used for this analysis can be found in the Appendix.

2.3. Statistical models

Repeated measures ANOVA models were developed using SAS for Windows v. 9.4 (SAS Institute Inc., Cary, NC, USA). For each model, participant was used as a blocking variable to allow for examining the differences due to jump type (free and restricted arm jumps) while excluding differences between participants. Differences between free and restricted arm jumps for all parameters were calculated using the "proc mixed" command in SAS with Bonferroni adjustments. Statistical significance was indicated for $p < 0.05$. Descriptive statistics were also conducted using the "proc means" command to obtain the mean ± 95% confidence intervals for each parameter for both jump types.

3. Results

3.1. Jump distance and center of gravity (CG) kinematics

Participants jumped 0.356 ± 0.071 m, or 29% farther ($p < 0.0001$), in free arm jumps (1.587 ± 0.156 m) than in restricted arm jumps (1.231 ± 0.097 m). Participants demonstrated larger CG velocity magnitudes at takeoff (3.20 ± 0.17 m/s vs. 2.83 ± 0.13 m/s, $p < 0.0001$), greater CG heights at takeoff (1.117 ± 0.011 m vs. 1.093 ± 0.011 m, $p < 0.0001$), greater lateral distances of the CG relative to the right foot at takeoff (0.324 ± 0.041 m vs. 0.252 ± 0.029 m, $p < 0.0001$), greater lateral distances of the left foot relative to the CG at landing (0.142 ± 0.017 m vs. 0.105 ± 0.013 m, $p < 0.0001$), and lower CG heights at landing (0.982 ± 0.019 m vs. 1.000 ± 0.012, $p = 0.0136$). The angle of the CG velocity at takeoff relative to direction of the jump showed no significant differences ($p = 0.6240$) between free arm (39.7 ± 1.6°) and restricted arm (39.2 ± 1.7°) jumps.

3.2. Work analysis

Total body work was 33% greater ($p < 0.001$) in free arm jumps (511 ± 59 J) than in restricted arm jumps (384 ± 37 J) (Table 1). Comparing individual joint work values, more work was performed in free arm jumps at eight of the 11 joints with the largest

Table 1
Work done at upper extremity (shoulder and elbow), lower back, and lower extremity (ankle, knee, and hip) joints (mean ± 95% CI).

	Free arms	Restricted arms	Difference	p-value
Upper extremity joints	45 ± 11 J	3 ± 2 J	42 ± 11 J	<0.0001
Lower back	52 ± 11 J	22 ± 7 J	31 ± 8 J	<0.0001
Lower extremity joints	414 ± 47 J	359 ± 34 J	54 ± 17 J	<0.0001
Total body	511 ± 59 J	384 ± 37 J	127 ± 27 J	<0.0001

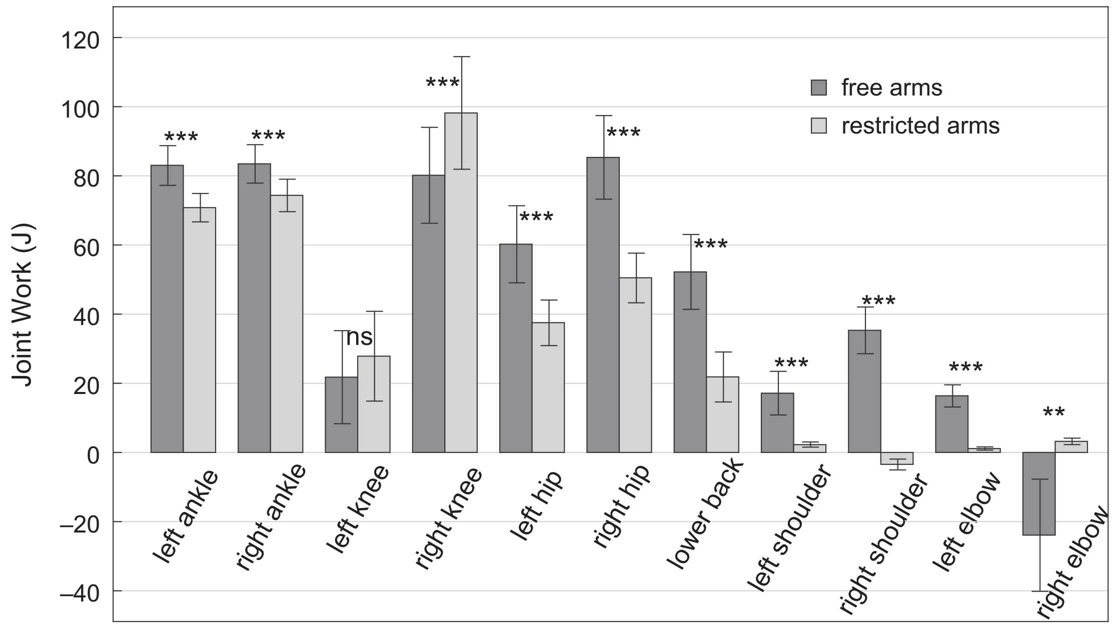

Fig. 2. Work done at all joints (J) for free and restricted arm jumps. ***: p < 0.001, **: p < 0.01, ns: p > 0.05.

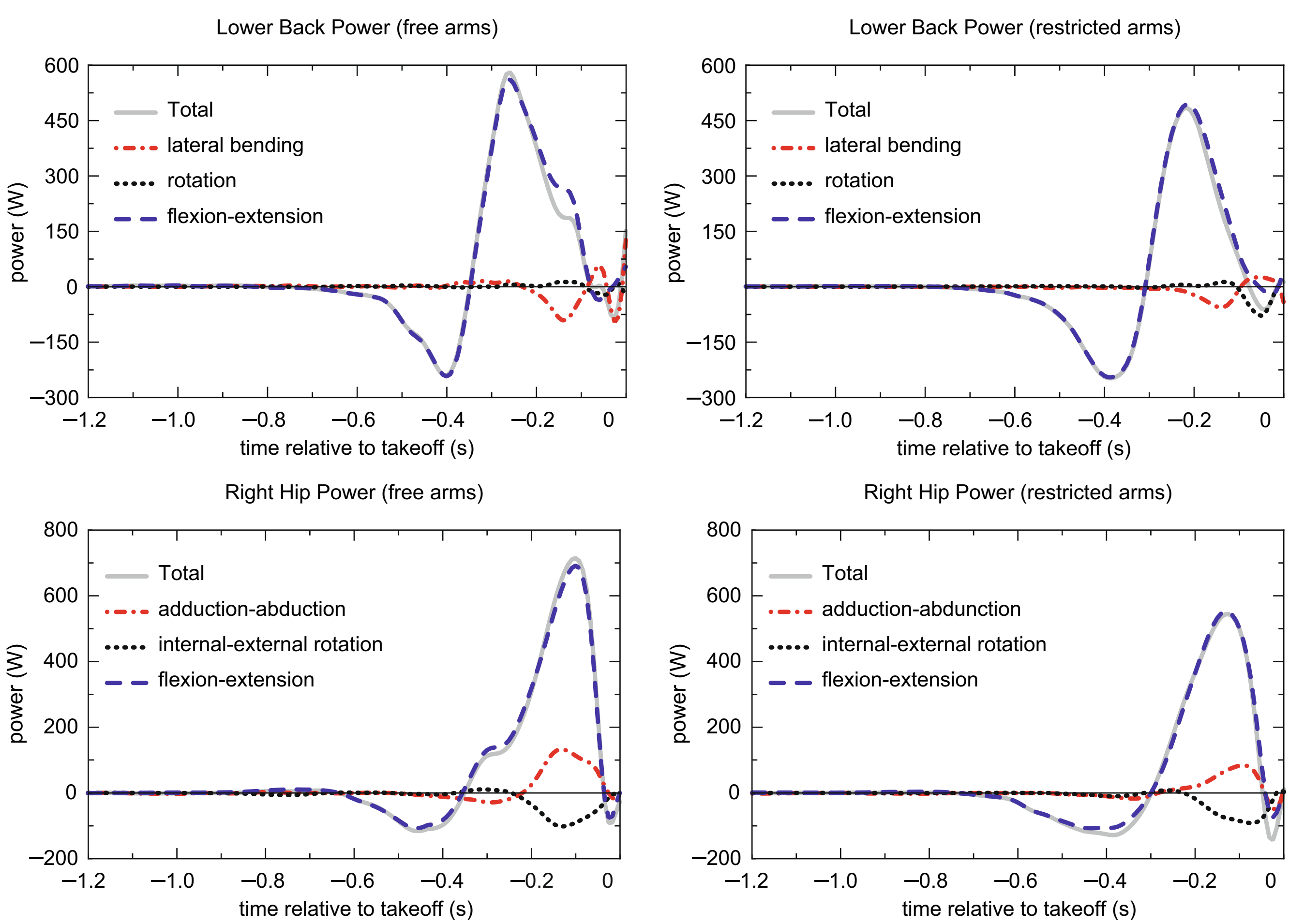

Fig. 3. Mean total power profiles for the lower back (top row) and right hip (bottom row) for free (left column) and restricted (right column) arm jumps during takeoff phase of jumps along with the power due to the moments about each of the three anatomical axes of the distal segment (i.e., pelvis for the lower back and right thigh for the right hip).

differences (>30 J) found at the lower back (52 ± 11 J vs. 22 ± 7 J, $p < 0.0001$), right hip (85 ± 12 J vs. 51 ± 7 J, $p < 0.0001$), and right shoulder (35 ± 7 J vs. −3 ± 2 J, $p < 0.0001$) (Fig. 2). Other joints with more work performed in free arm jumps included the left ankle (83 ± 6 J vs. 71 ± 4 J, $p < 0.0001$), right ankle (83 ± 6 J vs. 74 ± 5 J, $p < 0.0001$), left hip (60 ± 11 J vs. 38 ± 7 J, $p = 0.0001$), left shoulder (17 ± 6 J vs. 2 ± 1 J, $p < 0.0001$), and left elbow (16 ± 2 J vs. 1.1 ± 0.5 J, $p < 0.0001$). In restricted arm jumps, more work was performed over free arm jumps at the right knee (98 ± 16 J vs. 80 ± 14 J, $p = 0.0002$) and right elbow (3 ± 1 J vs. −24 ± 16 J, $p = 0.0027$). The work done at the left knee was not significantly different ($p = 0.1455$) for free (22 ± 13 J) and restricted (28 ± 13 J) arm jumps.

Of the 127 ± 27 J of extra work performed in free arm jumps compared to restricted arm jumps, 54 ± 17 J came from the six lower body joints (i.e., ankles, knees, and hips), 42 ± 11 J came from the four upper body joints (i.e., shoulders and elbows), and 31 ± 8 J came from the lower back joint (Table 1).

3.3. Power analysis for lower back and right hip

The largest increases in work performed for free arm jumps occurred at the lower back, right hip, and right shoulder. To test whether the joint torque augmentation theory can explain why upper extremity motion results in increased work at joints that are not in the upper body, further analysis of the power profiles of the lower back and right hip was conducted. Power profiles for the lower back and right hip (Fig. 3) demonstrate that the total power is well approximated by the power due to the moment about the flexion-extension axes. Based on this understanding, the analysis from here will only consider the moments, angular velocities, and power about the flexion-extension axes.

As already indicated (Table 1), 31 ± 8 J more work was performed at the lower back in free arm jumps compared to restricted arm jumps. Lower back flexion-extension power was greater in free arm jumps from about 0.4 s to 0.25 s before takeoff (Fig. 4). The lower back flexion-extension joint moment and angular velocity were also greater throughout this period for free arm jumps (Fig. 4).

In free arm jumps, 34 ± 8 J more work ($p < 0.0001$) was performed at the right hip. Right hip flexion-extension power was greater in free arm jumps from about 0.45 s to 0.25 s and from about 0.15 s to 0.05 s before takeoff (Fig. 5). Throughout these periods, the right hip flexion-extension joint moment was greater and the flexion-extension joint angular velocity was slightly greater or about the same for free arm jumps (Fig. 5).

4. Discussion

To provide greater understanding of the role of upper extremity motion in explosive lateral movements, this study tested two hypotheses: (1) that arm movement enhances lateral jumping distance and (2) that impart energy and joint torque augmentation theories can explain any improvement for lateral jumps as well.

The first hypothesis was clearly confirmed as participants jumped 29% (35.6 cm) farther in free arm jumps than in restricted arm jumps. Of the 35.6 cm improvement, 26% (9.4 cm) was due to the increase in the lateral and vertical CG position relative to the right foot at takeoff, 15% (5.3 cm) was due to the position of the CG relative to the left foot at landing, and 59% (21.0 cm) was due to the increase in CG velocity at takeoff. The greater velocity and height of the CG at takeoff was enabled by the 33% (127 ± 27 J) extra work performed by the body when free arm motion was allowed. 43% (54 ± 17 J) of that extra work came from the lower body joints, 33% (42 ± 11 J) came from the upper body joints, and 24% (31 ± 8 J) came from the lower back.

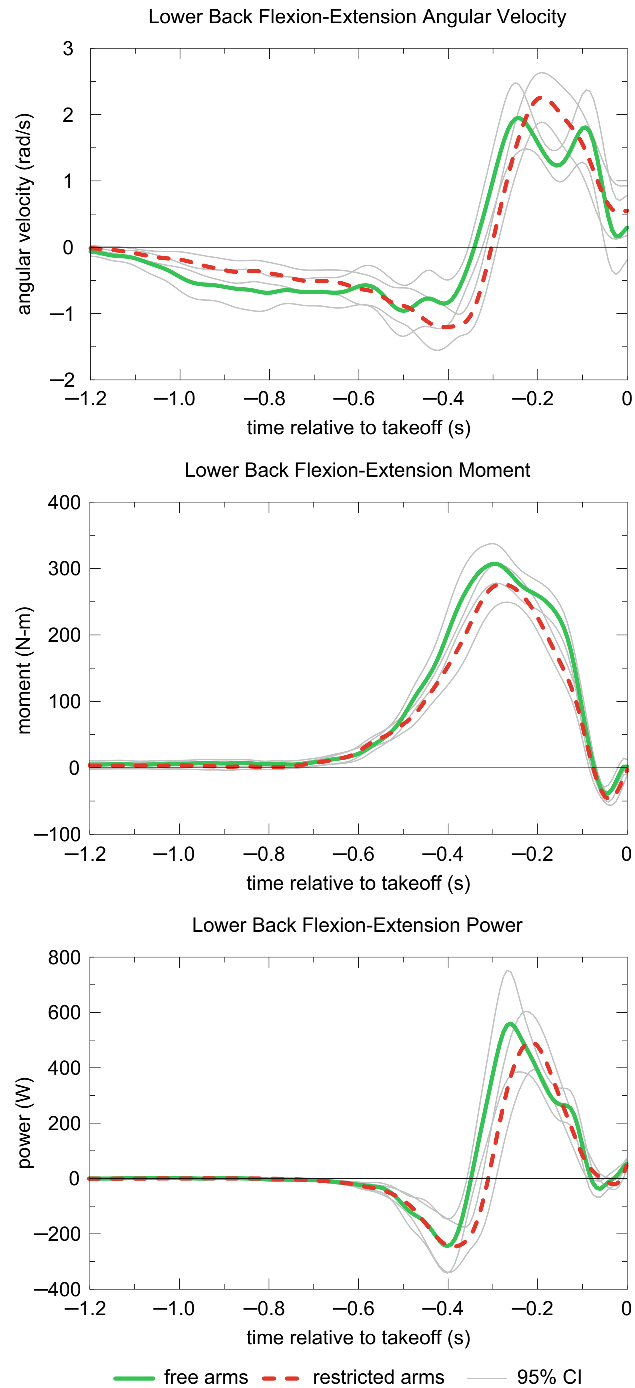

Fig. 4. Lower back angular velocity, moment, and power about flexion-extension axis (pelvis reference frame) during takeoff phase for free and restricted arm jumps.

Consistent with the impart energy mechanism that has been identified in standing forward (Ashby and Delp, 2006) and vertical (Lees et al., 2004) jumps, the ability to swing the arms in standing lateral jumps allowed the muscles crossing the shoulders and elbows to do 45 ± 11 J net positive work during takeoff, thereby adding energy to the system. The amount of work performed by upper extremity muscles in the present study is comparable to values reported for standing forward jump experiments of 22 J (Hara et al., 2008), 47 J (Ashby, 2004), and 77 J (Filush, 2012); for a standing forward jump simulation of 80 J (Ashby and Delp, 2006); and for standing vertical jump experiments of about 69 J (Lees et al., 2004).

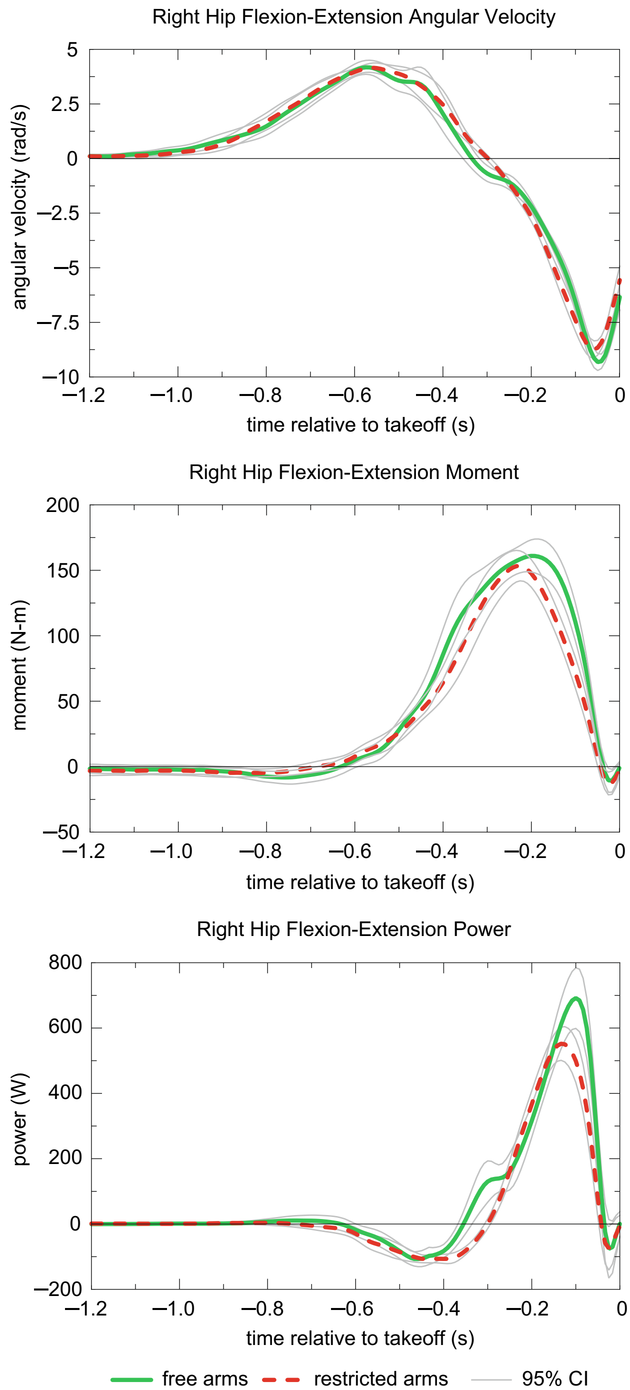

Fig. 5. Right hip angular velocity, moment, and power about flexion-extension axis (right thigh reference frame) during takeoff phase for free and restricted arm jumps.

After taking into account the extra work performed by upper extremity muscles, the approximately 85 J of remaining additional work when arm motion was allowed occurred at the lower back and lower extremity joints. The joint torque augmentation theory has been proposed as one explanation for this phenomenon for both forward and vertical standing jumps (Ashby and Delp, 2006; Cheng et al., 2008; Feltner et al., 1999; Harman et al., 1990). However, the data from the present study does not necessarily support joint torque augmentation as an explanation for the additional work performed at the lower back and lower extremity joints in free arm lateral jumps. The lower back and right hip were the only non-upper body joints to demonstrate greater than 30 J increase in work performed when free arm motion was permitted. As shown in Figs. 4 and 5, for the periods where joint power was greater at these two joints, the angular velocities were also greater, which means that the greater joint torque was not due to slower shortening velocities of extensor muscles at those joints.

If the increased lower back and lower extremity joint work in free arm jumps cannot be explained by joint torque augmentation, then what can explain it? The greater joint moments in free arm jumps compared to restricted arm jumps at any joint could be achieved through greater muscle activations, differences in muscle geometry including muscle lengths and moment arms, or even enhancements due to the stretch-shortening cycle of muscle. Due to the limitations of experimental motion capture, the present study was not able to address these questions regarding differences in individual muscle activations, lengths, or moment arms when arm motion was allowed and what effect those differences might have had on joint power or work. The greater moments achieved at the lower back and right hip demonstrated in Figs. 4 and 5 suggest that there were likely significant differences in the muscle activations. Prior researchers have suggested in forward standing jumps that individuals may "hold back" during the takeoff phase of jumps without arm movement due to the inability to rotate arm segments during the flight phase in preparation for landing (Ashby and Delp, 2006; Ashby and Heegaard, 2002). Perhaps a similar strategy was employed for the lateral jumps in the present study. Future work that measures electromyographic activity of key lower extremity and lower back muscles could provide insight into differences in muscle activation strategies for lateral jumps with and without arm movement. Greater insight could also be obtained with musculotendon actuated simulations which could identify the effect of arm swing on individual muscle activations, lengths, moment arms, and velocities. Such simulations could help determine whether available muscle power is not being utilized in jumps without arm movement to maintain balance and control throughout the movement.

Prior research into the role of arms in jumping has been conducted on symmetrical tasks like vertical and forward jumping. The asymmetrical nature of lateral jumping is demonstrated at the elbows in free arm jumps with the left elbows doing positive work (16 ± 2 J) and the right elbows doing negative work (−24 ± 16 J). Further analysis is needed to identify the exact reasons for this, but one potential explanation is that the left elbow may do positive work to improve performance while the right elbow does negative work to maintain stability and balance at key moments of the movement. The ability for the right elbow to move freely and do negative work to promote stability may enable muscles crossing other joints to more aggressively do positive work. The lack of this freedom in restricted arm jumps may require some "holding back" at other joints to maintain stability.

5. Conclusions

This is the first study to report on the role of free arm movement in lateral jump performance. The results demonstrated that jump distance was significantly increased with free arm movement with over 40% of that improvement due to the improved vertical and lateral positions of the body's CG at takeoff and landing. Simple arm positioning altered the body's CG enough to significantly improve performance, suggesting that sport training related to explosive lateral movements may consider emphasizing kinematics or motor control to be as important as strength and power training. With this small sample, the results should not be generalized to other sport movement patterns, so additional research is justified, particularly with studies examining the motor coordination of movements involving both upper and lower extremity segments. Since increased takeoff velocity of the CG contributed to almost 60% of the improvement in lateral jump distance, further research with experimental EMG and neuromuscular simulations is needed to explain the greater work performed by the lower extremities in lateral jumps with free arm movement.

Declaration of Competing Interest

There are no conflicts of interests to disclose.

Acknowledgments

Special thanks are given to the Statistical Consulting Center at GVSU for their help with the statistical analyses.

Appendix

Neglecting air drag, the projectile motion formula for the CG position in the vertical direction z can be used to calculate the flight time t of a jump:

$$z_{td} = z_{to} + v_{to}\sin(\theta_{to})t - \frac{1}{2}gt^2 \tag{A1}$$

where z_{td} is the CG height at touchdown, z_{to} is the CG height at takeoff, v_{to} is the magnitude of the CG velocity at takeoff, θ_{to} is the CG velocity angle with respect to the horizontal plane, and g is the gravitational acceleration constant. Solving this equation for the root that results in positive time gives:

$$t = \frac{v_{to}\sin(\theta_{to}) + \sqrt{v_{to}^2\sin^2(\theta_{to}) - 2g(z_{td} - z_{to})}}{g} \tag{A2}$$

The distance traveled during the flight phase of a jump x is equal to the horizontal component of CG velocity times the flight time. Thus, the equation for the horizontal distance traveling during flight is:

$$x = \frac{v_{to}\cos(\theta_{to})}{g}\left(v_{to}\sin(\theta_{to}) + \sqrt{v_{to}^2\sin^2(\theta_{to}) - 2g(z_{td} - z_{to})}\right) \tag{A3}$$

From this equation, it is clear that any variation to the magnitude or direction of the CG velocity at takeoff or the CG height at takeoff or landing results in different flight distance. The new flight distance x_1 that would result from varying one of these parameters can be estimated with Eq. (A3) by varying that single parameter while keeping the remaining parameters at their nominal values. The change in flight distance Δx that would result from varying one of these parameters is then simple this new distance x_1 minus the original distance x_0 calculated using the nominal values:

$$\Delta x = x_1 - x_0 \tag{A4}$$

For the analysis in this paper, the "nominal" values were the CG positions and velocities at takeoff and landing for restricted arm jumps. Each of the parameters was perturbed in turn by substituting in the values for the free arm jumps. In a complex human movement such as lateral jumping, the effects of varying these parameters would not be expected to be truly independent. Accordingly, the total contributions summed up to slightly more than the total improvement in flight distance actually observed. The relative contributions were then scaled down slightly in a proportionate manner so that they were consistent with the total improvement in flight distance.

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