Understanding how an arm swing enhances performance in the vertical jump

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Abstract

This investigation was conducted to examine the various theories that have been proposed to explain the enhancement of jumping performance when using an arm swing compared to when no arm swing is used. Twenty adult males were asked to perform a series of maximal vertical jumps while using an arm swing and again while holding their arms by their sides. Force, motion and electromyographical data were recorded during each performance. Participants jumped higher (0.086 m) in the arm swing compared to the no-arm swing condition and was due to increased height (28%) and velocity (72%) of the center of mass at take-off. The increased height at take-off was due to the elevation of the arm segments. The increased velocity of take-off stemmed from a complex series of events which allowed the arms to build up energy early in the jump and transfer it to the rest of the body during the later stages of the jump. This energy came from the shoulder and elbow joints as well as from extra work done at the hip. This energy was used to (i) increase the kinetic and potential energy of the arms at take-off, (ii) store and release energy from the muscles and tendons around the ankle, knee and hip joint, and (iii) ‘pull’ on the body through an upward force acting on the trunk at the shoulder. It was concluded that none of the prevailing theories exclusively explains the enhanced performance in the arm swing jump, but rather the enhanced performance is based on several mechanisms operating together.

Keywords: Arm swing; Vertical jump; Enhanced performance

1. Introduction

In the vertical jump, as well as in many sports skills, the arms are swung vigorously upward during take-off to enhance performance. Recent data (Feltner et al., 1999) have shown that 60% of the increased performance is due to an increase in take-off velocity. It has been widely reported that take-off velocity can be enhanced by 6–10% or more when using an arm swing (Luhtanen and Komi, 1979; Shetty and Etnyre, 1989; Harman et al., 1990). Despite this marked effect on performance, the mechanisms by which arm swing leads to an increase in take-off velocity have not been fully established.

Several theories have been proposed for the effect that arm swing has on take-off velocity. One of the earliest was the ‘transmission of force’ theory (Payne et al., 1968), which suggests that as the arms are accelerated upwards, a downward force is exerted through the body, instantly increasing the ground reaction force, which in turn leads to a greater impulse increasing the vertical velocity of the center of mass (CM). Although this idea has been repeated since (Dapena, 1993) it has never been specifically tested. Recent indirect evidence, however, from experimental (Harman et al., 1990) and simulation (Dapena, 1999) investigations have suggested that this may be too simplistic a view. A second theory, the ‘joint torque augmentation’ theory (Feltner et al., 1999), suggests that the reaction force acting on the trunk due to the upward acceleration of the arms causes the hip, knee and ankle joints to slow their rate of extension enabling them to produce greater muscle forces (Dapena and Chung, 1988; Harman et al., 1990). There has been little direct evidence to support this theory until the recent study by Feltner et al. (1999). They reported increased torques at the hip and knee joints during the propulsive phase of jumping when using an arm swing but do not specify how the increased muscle force...
may lead to enhanced performance. A third theory, the ‘pull’ theory, was suggested by Harman et al. (1990) who speculated that towards the later part of the jump, when the arms begin to decelerate, their high vertical velocity relative to the trunk enables them to pull on the trunk, transferring energy from the arms to the rest of the body. This theory appears not to have been identified by other authors and has not been investigated further.

It is surprising that there has been so little effort devoted to testing these various theories despite the obvious advantages arm swing has to jumping performance. Therefore, the purpose of this paper was to examine the theories and mechanisms that underpin enhanced performance in the vertical jump when using an arm swing.

\section{Method}

In order to investigate the theories referred to above an arm swing and a no-arm swing jump paradigm was used. Twenty-athletic adult males (mean ± S.D.: age = 19.9 ± 3.9 years; height = 180.0 ± 6.5 cm; mass = 75.4 ± 13.3 kg) participated in this investigation. All participants were competitively active in sports that ranged from field games play to gymnastics. All were fit and injury free and each gave informed consent as required by the University Ethics Committee.

\subsection{Data collection}

Participants were given the opportunity to warm up with light exercise and stretching, and to practice the two types of jump. They were required to perform six maximal counter-movement vertical jumps, three while using an arm swing and three with their hands placed on the pelvis with their thumbs located in a belt around the waist. Participants performed each jump on a force platform (Kistler, Winterthur, Switzerland). Reflective markers were placed over the second metatarsal–phalangeal joint; lateral malleolus, lateral knee, hip, wrist, and elbow joints, acromion process, C7 and on the vertex of the head using a marker placed on the top of a cap worn on the head. The 3D position of each marker was recorded using a 6-camera opto-electronic motion capture system (Prorreflex, Qualysis, Savedalen, Sweden). Electromyographical (EMG) recordings (TEL100, Bio Pac Systems, Goleta, CA, USA) were made from the rectus femoris, vastus lateralis, biceps femoris and gastrocnemius muscles. Data were collected for a period of 6s which allowed approximately 2s of quiet standing before the jump commenced. The motion data were collected at 240 Hz while the force and EMG data were collected at 960 Hz. All data were electronically synchronized in time.

\subsection{Data reduction}

The 3D motion data from the 16 markers were used to define a 12 segment biomechanical model using segmental data from Dempster (1955) for adult males. The angles at the ankle, knee and hip were defined as the minor (i.e. flexion) angles at these joints. The trunk was considered a rigid segment and its orientation defined to the vertical. All kinematic data were smoothed using a Butterworth fourth-order zero-lag filter with padded end points (Smith, 1989) and a cut off frequency of 7 Hz based on a residual analysis and qualitative evaluation of the data. Derivatives were calculated by simple differentiation (Winter, 1990). As vertical jumping is essentially a sagittal plane activity, data were projected onto the sagittal plane in order to compute kinematic variables.

The kinematic data were used to define the energy state of the arms system that was computed as the sum of the potential energy (PE) and linear and rotational kinetic energies of the three segments of the arm. As the interest in this investigation was with the energy transfers into and out of the arms system through its attachment with the trunk at the shoulder joint (assumed a fixed point), arm segment height and velocity were defined relative to the shoulder. The energy state of the head–trunk–legs system was defined in a similar way although for that calculation the height and velocity relative to the external reference frame were used. The total body linear kinetic energy (KE) and PE energy were computed from the height and velocity of the CM.

The force data were averaged over four adjacent points so that each force value corresponded to each motion data value at 240 Hz. As no marker was placed on the hand, the wrist was assumed to be at a fixed angle of 180° to the forearm. Inverse dynamics using standard procedures (Miller and Nelson, 1973; Winter, 1990) was used to compute the segment proximal and distal net joint force components and the net joint torques at the ankle, knee, hip, wrist, elbow and shoulder. Joint power and work done were calculated based on standard procedures (de Koning and van Ingen Schenau, 1994). Extension joint torques are presented as positive, while flexion joint torques are negative. Similarly, joint power generation is presented as positive while joint power absorption is negative. A further variable was found useful when interpreting the data and defined as the shoulder load torque. This variable represented the torque about the hip due to the torques and forces acting at the shoulder. It was calculated as the sum of the net shoulder joint torque plus the torque about the hip due to the horizontal and vertical net joint forces at the shoulder. For all joint variables the mean of the left and right limbs was computed.
The raw electromyographical EMG signal was high-pass filtered (Murphy and Robertson, 1994) at 10 Hz and low-pass filtered (Winter, 1990) at 350 Hz using Butterworth fourth-order zero-lag filters with padded end points. The data were then rectified and further smoothed using a 10 Hz low-pass Butterworth fourth-order zero-lag filter.

All kinetic variables were normalized to body mass. The start and end of the counter-movement was defined when the vertical ground reaction force went above or below a threshold value of 40 N and was also used to define the movement time (MT) of the action. For each variable of interest the data set was normalized to 100 points by linear interpolation. Each normalized set was averaged over all participants and all trials (total 60 data sets) to provide a mean curve for that variable.

2.3. Statistical analysis

Statistical procedures used were the Kolmogorov–Smirnov test for establishing the normality of data sets and Student’s t-test for establishing differences, except where data were non-normal in which case the Wilcoxon-Signed Ranks test (statistic Z) was used. A value of \( p < 0.05 \) was used to indicate statistical significance.

3. Results

The arm swing jump produced a greater height raised by the CM at take-off by 0.024 m and by 0.086 m at the apex of the flight (Table 1). The velocity of take-off was 0.23 m/s (8.9%) higher and is in good agreement with previous findings. The maximum trunk inclination was 5° greater in the arm swing jump indicating that the trunk went through a greater range of motion. The total work done in moving the CM from its lowest point during the descent phase was greater (but not significantly) in the arm swing jump due to the arms being hyper-extended. For most of the ascent phase (Fig. 2b) the upward vertical velocity of the CM was lower for the arm swing jump with the enhanced vertical velocity of the CM only evident after 92% MT. The trunk (Fig. 2c) began its change of direction earlier in the arm swing jump (59% MT) compared to the no-arm swing jump (63% MT). The vertical ground reaction force (Fig. 2d) was greater as the arms were hyper-extended in the arm swing jump, lower during the late descent and early ascent phases but larger again from about 82% MT.

The hip joint showed a greater angular extension velocity during the late descent phase with arm swing (50–75% MT, Fig. 3c) reflecting its earlier onset of extension. All joints showed a smaller angular velocity during the early ascent phase with arm swing (Fig. 3a–c) but greater angular velocity during the late ascent phase (95–100% MT). Joint torques were characteristically smaller during the late descent phase with arm swing (Fig. 4a–c) but significantly greater during the ascent phase (78–100% MT). At the point of maximum difference during the ascent phase, the data were all significantly different (ankle \( Z = 6.68, p < 0.001 \); knee \( Z = 5.12, p < 0.001 \); hip \( Z = 5.99, p < 0.001 \)). With regard to joint power, the ankle and knee joints showed a lower power generation over the early ascent phase (Fig. 5a,b from 78–90% MT) but a greater power generation over the late ascent phase (90–100% MT). The hip joint showed power generation to occur earlier in the arm swing jump.

| Table 1 |
| Performance variables (mean ± s) for the arm swing and no-arm swing jumps |

<table>
<thead>
<tr>
<th></th>
<th>Arm swing</th>
<th>No arm swing</th>
<th>t</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing height (m)</td>
<td>1.050 ± 0.049</td>
<td>1.050 ± 0.046</td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Low point (m)</td>
<td>−0.297 ± 0.057</td>
<td>−0.299 ± 0.057</td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Height at TO (m)</td>
<td>0.140 ± 0.049</td>
<td>0.116 ± 0.046</td>
<td>17.09</td>
<td>( p &lt; 0.001 )</td>
</tr>
<tr>
<td>Maximum height (m)</td>
<td>0.532 ± 0.043</td>
<td>0.446 ± 0.037</td>
<td>12.48</td>
<td>( p &lt; 0.001 )</td>
</tr>
<tr>
<td>Minimum velocity (m/s)</td>
<td>−1.07 ± 0.21</td>
<td>−1.13 ± 0.20</td>
<td>5.10</td>
<td>( p &lt; 0.001 )</td>
</tr>
<tr>
<td>Velocity at TO (m/s)</td>
<td>2.81 ± 0.14</td>
<td>2.58 ± 0.14</td>
<td>9.45</td>
<td>( p &lt; 0.001 )</td>
</tr>
<tr>
<td>Trunk flexion angle(deg)</td>
<td>44.8 ± 9.5</td>
<td>39.5 ± 9.7</td>
<td>3.69</td>
<td>( p &lt; 0.002 )</td>
</tr>
<tr>
<td>Duration of action (s)</td>
<td>0.96 ± 0.14</td>
<td>0.86 ± 0.14</td>
<td>4.48</td>
<td>( p &lt; 0.001 )</td>
</tr>
</tbody>
</table>

NS = Non-significant.

*Relative to standing height.
(Fig. 5c), but lasted for as long as the no-arm swing jump, thus enabling it to perform more work (Table 2). At the point of maximum difference during the ascent phase the data were all significantly different (ankle $Z = 5.64$, $p < 0.001$; knee $Z = 3.74$, $p < 0.001$; hip $Z = 3.195$, $p = 0.001$). Two periods of greater work were done in the arm swing jump (Fig. 5d) corresponded to the period where the hip joint was generating more power (60–80% MT) and the late ascent phase (90–100% MT) where the hip, knee and ankle joints generated their greater power. The trough between these two peaks (80–90% MT) represents a reduction in work done during the arm swing jump, and this corresponded to the lower power output of the hip, knee and ankle joints due to their lower angular velocities. These lower angular velocities also coincided with greater joint torques but the combined effect was a reduced power generation.

The net joint forces and torques at the shoulder (Fig. 6a–c) showed little difference during arm hyper-extension between the two types of jump. Once the forward arm swing began the vertical net joint force at the shoulder initially reduced then increased. The accelerating torque at the shoulder began at 60% MT

<table>
<thead>
<tr>
<th></th>
<th>Arm swing (J/kg)</th>
<th>No-arm swing (J/kg)</th>
<th>Difference (J/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE at take-off$^b$</td>
<td>1.37</td>
<td>1.14</td>
<td>+0.23</td>
</tr>
<tr>
<td>KE at take-off$^b$</td>
<td>3.95</td>
<td>3.33</td>
<td>+0.62</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>+0.85</td>
</tr>
<tr>
<td>Total WD$^{a,b}$ (low point-apex)</td>
<td>8.13</td>
<td>7.31</td>
<td>+0.82</td>
</tr>
<tr>
<td>WD + at ankle</td>
<td>2.06 ± 0.35</td>
<td>2.03 ± 0.31</td>
<td>+0.03</td>
</tr>
<tr>
<td>WD + at knee</td>
<td>1.94 ± 0.47</td>
<td>1.94 ± 0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>WD + at hip</td>
<td>3.24 ± 0.62</td>
<td>2.84 ± 0.78</td>
<td>+0.40</td>
</tr>
<tr>
<td>WD + at shoulder</td>
<td>0.63 ± 0.26</td>
<td>0.03 ± 0.02</td>
<td>+0.60</td>
</tr>
<tr>
<td>WD + at elbow</td>
<td>0.28 ± 0.16</td>
<td>0.00 ± 0.01</td>
<td>+0.28</td>
</tr>
<tr>
<td>Total WD at joints</td>
<td>8.15</td>
<td>6.84</td>
<td>1.31</td>
</tr>
</tbody>
</table>

$^a$Calculated from WD = m.g.h.  
$^b$Computed from data in Table 1.
Fig. 2. Averaged time-normalized graphs for arm swing (AS, thick line) and no-arm swing (NAS, thin line) for (a) center of mass height (b) center of mass vertical velocity (c) trunk angle and (d) vertical ground reaction force. The graphs on the right-hand side represent the difference between the AS and NAS jumps.

Fig. 3. Averaged time-normalized graphs for arm swing (AS, thick line) and no-arm swing (NAS, thin line) for (a) ankle angle (b) knee angle and (c) hip angle. The graphs on the right-hand side represent the difference between the AS and NAS jumps.
At this point the horizontal net joint force began to increase. Once the arms passed the vertical position (78% MT) the vertical net joint force began to reduce from its peak value and the horizontal net joint force and muscle torque became negative. The combination of these forces and torques served to substantially increase the energy of the arms but also had a significant effect on the trunk, illustrated in Fig. 6d as the shoulder load torque acting at the hip. This was less negative during the late descent phase (60–74% MT) in the arm swing jump and would allow the trunk extension velocity to increase more rapidly than it would in the no-arm swing jump. Consequently the hip joint would be able to engage in faster muscle contractions and deliver greater power, as noted above. Once the arms passed the vertical in the arm swing jump, the shoulder load torque acting on the trunk became more negative (74–90% MT) which had the effect of slowing the angular velocity of the hip joint and reducing its power output (Fig. 5c). The shoulder load torque on the trunk became positive at about 90% MT, where the knee and ankle began their greater power generation. At this point the vertical net joint force at the shoulder became negative (Fig. 6a) and the corresponding positive net joint force acting on the trunk served to ‘pull’ the trunk upwards which in turn enhanced the extension velocity of the hip, knee and ankle joints (Fig. 3a–c). The positive work done at the shoulder joint (Fig. 6e) was 0.63 J/kg, all of which was delivered before the arms reached their downward vertical position. The negative work done at the shoulder was 0.83 J/kg and occurred during the upward phase of arm motion. The positive work done at the elbow (Fig. 6f) was 0.28 J/kg and spanned both the downward and upward motions of the arms with approximately half being done over each phase.

As the arms moved forward from their hyper-extended position their KE relative to the shoulder increased rapidly to peak at 1.32 J/kg at 78% MT (linear = 1.2 J/kg, rotational = 0.12 J/kg). As the arms passed the vertical their KE decreased during the ascent to 0.1 J/kg (linear = 0.09 J/kg, rotational = 0.01 J/kg). Approximately 0.30 J/kg of PE was required by the arms to move from their lowest to their highest position at take-off. Thus, 0.4 J/kg was retained by the arms, leaving 0.92 J/kg of energy dissipated, and it is likely that this was transferred back into the trunk. However, the total energy of the head, trunk and legs system (Fig. 7e) showed a marked decrease in the arm swing jump during 78–90% MT but an increase from 90–100% MT. This suggests that the energy dissipated from the arms system is stored in the head, trunk and legs system as elastic energy that may then be recoverable during the later part of the movement.

All muscles (Fig. 8) showed a rise in activity from about 40% MT and reached a peak around 70–80% MT
which corresponded to the end of the descent and start of the ascent phases. At the point of maximum difference in muscle activity during the ascent phase, the data were significantly greater in the vastus lateralis ($Z = 2.61$, $p = 0.009$) and significantly lower in the biceps femoris ($Z = 3.50$, $p < 0.001$), but not significantly different in the gastrocnemius ($Z = 1.53$, $p = 0.125$) or rectus femoris ($Z = 1.92$, $p = 0.054$). The pattern of these differences suggests that there was some interaction between muscle activity and arm swing, particularly for muscles acting at the hip joint.

4. Discussion

Using an arm swing when performing a counter-movement vertical jump has enhanced performance by increasing the height of the CM at take off and by increasing its take-off velocity. The increase in height of the CM at take-off (0.024 m, 28%) is due to the influence of arm position on the location of the CM. The increase in take-off velocity (0.062 m, 72%) is in agreement with, but slightly in excess of, the 60% reported by Feltner et al. (1999).

The increase in take-off velocity is due to a complex series of events which begin at the start of the movement but manifest themselves towards the very end of the movement, and can be described as the jump unfolds. The trunk is inclined further forwards in the arm swing jump which enables it to extend earlier and faster (59% MT) than in the no-arm swing jump (63% MT), to generate power over a longer period and so do more work. The greater work done at the hip (0.4 J/kg) does not increase the energy of the head–trunk–legs system, but is transferred to the arms and serves to increase their energy. The KE build up in the arms is substantial and comes from three sources: (i) PE of the arms, (ii) positive work done by the muscles at the shoulder and elbow joints, and (iii) positive work done by the trunk on the arms. Once the arms have moved beyond the vertical (78% MT) their energy declines by a reversal of the same three processes. It is unlikely that the energy dissipated from the arms is lost, but it could be stored in the muscles and tendons of the lower limb joints. Once the
Fig. 6. Averaged time-normalized graphs for arm swing (AS, thick line) and no-arm swing (NAS, thin line) for shoulder (a) vertical and (b) horizontal net joint force and (c) torque; (d) shoulder torque load (e) shoulder power and (f) elbow joint power. The graphs on the right-hand side of (a) and (d) represent the difference between the AS and NAS jumps.

Fig. 7. Averaged time-normalized graphs for arm swing (AS, thick line) and no-arm swing (NAS, thin line) for the energy of the arms relative to the shoulder joint (a) KE (b) rotational KE (c) PE and (d) total energy; (e) the trunk and legs total energy. The graphs on the right-hand side of (e) represents the difference between the AS and NAS jumps.
arms have moved beyond the horizontal (90% MT) the vertical net joint force at the shoulder produces an upward force (or pull) on the trunk which signals the rapid change in many of the variables including a return of energy stored in the immediately preceding phase. There is an increase in the knee and ankle joint angular velocities to compliment the already elevated joint torques, and as a result, an increased power output. Consequently, the enhanced performance in the arm swing compared to the no-arm swing jump seems to be explained by the work done by the muscles of the shoulder and elbow joints together with the extra work done at the hip joint which are all used to build up the energy in the arms. The energy in the arms is used initially to work against the body, temporarily storing energy, to ‘pull’ on the body during which time the stored energy is released, and to increase the PE and KE of the arms at take-off.

Energy accounting for the whole body system can be used to support the description of the events above, although some assumptions need to be made. One is that the energy of the jump originates from the positive power produced at the major lower limb joints and there are no energy sources from other joints in the body. A second is that there are no power losses due to the sequential nature of joint power production where one joint produces power while another joint absorbs power. A third is that there is no significant effect from treating the segments as rigid bodies with hinge joints. For the arm swing jump, the work done by the ankle, knee and hip joints (7.24 J/kg) is insufficient to explain the energy required to raise the CM to its apex (8.13 J/kg). However, if the work produced by the shoulder and elbow joints is now included, the total (8.15 J/kg) is remarkably close to that required, so it is likely that all of this energy is used to enhance the jump. One would expect the work done by the joints to exceed the work done in raising the CM, due to the rotational energy of the segments during extension. Hatze (1998) has suggested that in the vertical jump some 3% of total

\[ \text{(a) Rectus Femoris} \]
\[ \text{(b) Vastus Lateralis} \]
\[ \text{(c) Biceps femoris} \]
\[ \text{(d) Gastrocnemius} \]

Fig. 8. Averaged time-normalized graphs for arm swing (AS, thick line) and no-arm swing (NAS, thin line) for the EMG activity of (a) rectus femoris (b) vastus lateralis (c) biceps femoris and (d) gastrocnemius. The graphs on the right-hand side represent the difference between the AS and NAS jumps.
body energy may be attributed to non-vertical power components which include rotational energy. The fact that this is not apparent in the data may be a reflection of error in data values and provides an indication of the error magnitude. Energy accounting for the no-arm swing case is less successful as the energy produced by the lower limb joints (6.81 J/kg) fails to explain the energy required to raise the CM to its apex (7.31 J/kg). The discrepancy is outside the expected error range and so it may be that during the no-arm swing jump energy is produced from other joints. One possible candidate for this is the neck, as the head can be used as an extra segment. Calculations, which were undertaken but not reported in detail, show that the neck yielded a positive work done of 0.08 J/kg (it was close to zero in the arm swing jump). A second is the extension of the trunk segment about the thoracic and lumbar spine junction, but no estimation of this could be made. A third unaccounted source of energy is to do with the elevation of the shoulders in the no-arm swing jump. The vertical net joint force at the shoulders reaches over 3 N/kg and as the shoulder may be elevated by as much as 0.10–0.15 m then up to 0.45 J/kg of work could be done. If these figures were added to the work done at the ankle, knee and hip for the no-arm swing jump the energy total is sufficient to raise the CM to its apex, and so it is likely that these techniques are used to aid the no-arm swing jump when the greater benefit from the arm swing is unavailable. If this were the case then this extra source of energy should be discounted and, using just the work done at the joints for a comparison, the true difference between the two jumps is 1.31 J/kg (Table 2).

Energy accounting for the arms system (i.e., relative to the shoulder joint) illustrates how the extra energy produced by the arms during the arm swing jump is used. The energy in the arms is progressively built up until at 78% MT the arms possess 1.32 J/kg KE. This energy comes from the PE of the arms in their retracted position (0.25 J/kg, Fig. 7c) plus the external work done by the shoulder muscles (0.63 J/kg) and approximately 50% of the internal work done by the elbow muscles (0.14 J/kg). The remaining energy requirement (0.30 J/kg) must come from the external work done by the forces acting at the shoulder joint due to their interaction with the trunk. The surplus power generated at the hip in the arm swing jump as the arms are brought forward and downward (54–78% MT, Fig. 5c, AS–NAS) produces 0.31 J/kg of work and so it is likely that this is the source of the extra energy required. During the phase from when the arms have passed their low point (78% MT) to take-off, the arms retain 0.4 J/kg of energy (0.3 J/kg as PE and 0.1 J/kg as KE) and so dissipate 0.92 J/kg of energy (Fig. 7a). However, a further 0.14 J/kg of internal work is done at the elbow joint (the remaining 50% of its work done), during this period and so a total of 1.06 J/kg is dissipated. The negative work done at the shoulder joint due to the shoulder joint torque is 0.83 J/kg which leaves 0.23 J/kg available for dissipation through the work done by the forces acting at the shoulder joint by ‘pull’. It has been suggested that the negative work done at the shoulder joint due to the shoulder joint torque is dissipated through working against the joints to store elastic energy that is later recovered. The extra energy released by the ankle and knee joints in the arm swing (from the integral of the AS–NAS power curve for the ankle, knee and hip joints from 90–100% MT) jump is estimated as 0.35 J/kg.

A first estimate of the work done by pull has been made as 0.23 J/kg. A second value can be obtained from a consideration of the vertical net joint force at the shoulder multiplied by the distance moved by the shoulder joint, and this is estimated as 0.46 J/kg. The two values obtained provide a lower and upper boundary for what energy may be dissipated through this mechanism. One must add these values to the residual potential and kinetic energy of the arms (0.4 J/kg) and the recovered elastic energy (0.35 J/kg), to give a lower and higher estimate of the energy benefit of the arm swing jump as 0.98 and 1.21 J/kg, respectively. These agree fairly well with the energy benefit of the arm swing jump which was 0.82 J/kg when based on the difference in performance of the two jumps, but 1.31 J/kg when based on the work done at the joints (Table 2). The difference between the lower and upper estimates can be partially resolved if the third energy transfer mechanism previously identified (i.e., work done by the trunk on the arms) is considered in more detail during the arm elevation phase. This provides an energy inflow to the arms system at the same time as energy is being dissipated through the shoulder joint torque and against gravity. The energy inflow to the arms from the body would lead to a reduction of body energy and this is seen during the critical period 78–90% MT (Fig. 7e), with the energy lost by the head–trunk–legs system being approximately 0.19 J/kg. If this energy was flowing into the arms then approximately 0.42 J/kg would be available for dissipation through pull during the later part of the movement (90–100% MT). A clarification of the exact power flows requires more detailed investigation, but this does suggest that the higher estimate is a more reasonable figure to use for future calculations. A second aspect which should be considered is the role of active muscle contraction. Muscle activity may be a means for compensating for energy conversion losses as well as for increasing the energy of the system. Over the whole movement, the levels of activity in the arm swing jump increase in the gastrocnemius (12%) and vastus lateralis (5%), while they decrease in the rectus femoris (−5%) and biceps femoris (−19%). It is difficult to establish the precise effect that this will have. The
increase in the gastrocnemius activity would be expected to increase joint torque at the ankle and reduce it at the knee. Similarly, the reduction in biceps femoris activity would reduce joint torque at the hip and allow an increase at the knee. However, there was no greater work done at the ankle or knee so it is likely that the changes in muscle activity of gastrocnemius may be used to overcome the energy losses associated with the energy transfer process and/or as a consequence of the coordination and balance requirements of the activities, but not, it seems, to contribute in any substantial way to the total work done during the arm swing jump.

It is now possible to comment on the various theories proposed for the enhanced performance when using an arm swing. The first theory (the transmission of force theory) must be rejected because the vertical net joint force at the shoulder, (Fig. 6a, AS–NAS), is not instantly and accurately reflected in the vertical ground reaction force (Fig. 2d, AS–NAS). There is little similarity in either the shape or magnitude of these curves, although there is some suggestion of a related but time delayed response from the application of a vertical force at the shoulder to its appearance in the ground reaction force. This might be expected if the force created by the arms served to affect the working conditions of the muscles and through this affected the changes in the vertical ground reaction force. The second theory (the joint torque augmentation theory) is also rejected. It is clear that there are substantial changes in lower extremity joint angular velocities, torques and powers which are related to arm swing. The augmentation theory predicts an increase in extensor torque during the period when the arms are accelerating upward. This has been reported by Feltner et al. (1999) as well as having been found in this study, and supports the widely held belief that the motion of the arms can directly influence the force–velocity characteristics of the lower limb muscles. However, the implication of the theory, although not stated by the authors promoting this theory, is that the increased joint torque leads to increased performance through an increase in the joint angular velocity, but this has been shown to not be the case. During the first half of the ascent phase of the arm swing jump (80–90% MT) where the muscle torque is greater, the joint velocity is lower, which leads to a reduced joint power and reduced performance over this period. It has been found in this study that the augmentation of joint torque is associated with the period during which the muscles and tendons of the joint are storing energy and a greater joint torque would facilitate this. Thus, joint torque augmentation is actually associated with energy storage and it is the later return of this energy that enhances performance, rather than the direct application of increased torque. The third theory (‘pull’ theory) is partially supported by the results of this study. When the arms move beyond the horizontal position the vertical net joint force at the shoulder is an upward force (or pull) acting on the trunk, reducing the energy of the arms and increasing the energy of the rest of the body.

5. Conclusion

The enhancement of performance when jumping using an arm swing is due to increased height (28%) and velocity (72%) of the CM at take-off. The increased velocity stems from a complex series of events that allows the arms to build up energy early in the jump and transfer this energy to the rest of the body during the later stages of the jump. The energy built up by the arms (1.32 J/kg) comes from the shoulders and elbow as well as extra work done at the hip. This energy was used (i) to increase the KE and PE of the arms at take-off, (ii) to store and release energy from the muscles and tendons around the ankle, knee and hip joints, and (iii) to increase the energy of the rest of the body through the transmission of force directly to the body through the shoulder joint. None of the prevailing theories exclusively explains the enhanced performance in the arm swing jump, but rather the enhanced performance is based on several mechanisms operating together. The energy benefit of using and arm swing was estimated between 0.98 and 1.21 J/kg, with the upper value being thought more reasonable. This was greater than the energy difference between the two types of jump and led to the suggestion that in the no-arm swing jump, where the energy build-up mechanisms identified above are not available, some extra work is done.

References