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Arm Swing during Vertical Jumps does not Increase EMG Activity of the Lower Limb Muscles

RESEARCH

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ABSTRACT

Arm swing improves vertical jump height but the underlying mechanism is not well understood. We assume that the negative acceleration of arm swing can increase the load and tension of the lower limb's extensor muscles enhancing force output and resulting in higher jump. The purpose of this study was to examine how arm swing affects the EMG activity of the lower limb muscles during vertical jumping in relation to the arm swing kinematics.

Sixteen physically active male college students were asked to perform squat (SJ) and countermovement jumps (CMJ) with arms akimbo and with arm swing. Jumps were carried out on a force platform while kinematic data and EMG activity of the right lower limb were measured.

Jumping height increased by 33% in SJ and by 18.9% in CMJ when performed with arm swing. In SJ with arm swing the vertical ground reaction force (GRF) was larger during the negative acceleration of the arm (71–91% of the jump, $p < 0.001$) with significantly slower relative joint extension. Similarly, in CMJAS during the negative acceleration of the arm vertical GRF was larger (89–97% of the jump, $p < 0.001$) compared to CMJ. Arm swing increased the jump time, net impulse and take off velocity in both jumps. No differences were detected in EMG between jumps carried out with and without arm swing.

When jumps carried out with arm swing, we can observe higher vertical GRF during the negative acceleration of the arm swing that indicate higher load on the lower limb, but we cannot confirm our initial idea with the results of the EMG comparison. Increase in jump height can be explained by the extended jump time resulting in greater mechanical variables in jumps with arm swing.

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INTRODUCTION

Squat jump (SJ) and countermovement jump (CMJ) are widely used vertical jump tests to assess athletic performance (Castagna & Castellini, 2013; Hébert-Losier et al., 2014; Moran et al., 2017; Petrigna et al., 2019), and the mechanical properties of the lower limb extensor muscles (Bobbert et al., 1996; Bobbert & Casius, 2005; Bobbert & van Ingen Schenau, 1988; Finni et al., 2000; Fukashiro et al., 1995; Kyröläinen & Komi, 1995). SJ is performed from a stationary semi-squat position held for approximately three seconds and then followed by extending the hip, knee and ankle joints as quickly as possible without any countermovement (Van Hooren & Zolotarjova, 2017). In contrast, CMJ starts from a standing position and initiates with a downward movement into a semi-squat position which is immediately followed by the quick extension of the lower limb joints (Van Hooren & Zolotarjova, 2017).

These jumps can be performed with and without arm swing. It has been well documented that using arm swing during vertical jumps increases the jump height compared with jumps performed without an arm swing (Feltner et al., 1999; Hara, Shibayama, Arakawa, et al., 2008; Lees et al., 2004; Mosier et al., 2017, 2019; Vanrenterghem et al., 2008). Several ideas have been proposed to explain how arm swing enhances vertical jump height, however, the mechanism behind arm swing and how it affects jumping performance is not fully understood. According to some earlier studies (Dapena, 1993), upward arm swing transmits force to the ground through the body, which increases vertical ground reaction force (GRF) and accordingly impulse resulting eventually in a higher jumping height. Supporting this idea, Mosier et al. (2017) found that about 1/3 of the resultant GRF is attributed to arm swing. Feltner et al. (1999) used a different approach and suggested that the GRF acting on the trunk during arm swing slows down the extension of the hip, knee and ankle joints enabling GRF to be exerted for a longer time resulting in a greater jump height. Hara et al. (2008) explained the higher peak jump height achieved with arm swing during SJ with the larger muscle work of the hip and leg extensor muscles, which possibly comes from the additional load on the lower limb induced by the arm swing.

A third idea was proposed by Harman et al. (1990). The authors used the "pulling theory" to explain the increased jump height. When arm swing starts to decelerate the high arm segment velocity enables to "pull" the body i.e., transferring energy from the arms to the body. In contrast to these ideas Lees et al. (2004) suggested that none of the aforementioned theories can explain the effect of the arm swing on jump height alone. More likely multiple factors jointly may alter the force-time pattern when jumps are carried out with arm swing, while the efficacy of the latter to increase jumping performance depends also on coordination and technique. For example, countermovement and arm swing has been shown to affect lower limb work and jumping height differently (Bobbert & Casius, 2005; Hara, Shibayama, Takeshita, et al., 2008). More specifically, arm swing increased lower limb work output during push-off and consequently the jump height, while countermovement resulted in a higher hip torque in the late barking phase possibly enabling a higher active state with countermovement than without countermovement (Hara, Shibayama, Arakawa, et al., 2008).

It has been also described that arm swing acts differently on the net torque of the lower limb's joints. For example, Hara et al. (2008) found higher torque at the same joint angle in the hip and ankle, but not in the knee joint for CMJAS compared with CMJ without arm swing. Arm swing may also induce slower extension of the hip, probably because of the increased load on the lower extremities (Hara, Shibayama, Takeshita, et al., 2008). Mosier et al. (2017) suggested that during countermovement jump with arm swing the longer jumping time occurs at the concentric phase and this presumably enables greater torque generation in the hips and ankles likely increasing jump height.

Considering the additional load on the lower limb's musculature when using arm swing a higher muscle tension would be expected. However, studies including measurements of the lower limb muscles' electromyographic (EMG) activity have reported ambiguous results. For example, Lees et al. (2004) found higher EMG activity in vastus lateralis and lower activity in biceps femoris during the push-off in CMJAS compared with CMJ indicating a greater hip joint work. Conversely, there was not any difference in gastrocnemius EMG activity, despite the greater ankle joint torque during late push-off when using arm swing. Although these studies conclude that arm swing can increase ankle and hip joint work and lower limb muscles activation, there is no consensus on how kinetic changes are connected with changes in the EMG activity.

The purpose of this study was to further investigate the effect of arm swing on lower limb muscles EMG activity during SJ and CMJ in relation to the kinematic changes of the arm swing and of the lower limb movement. We can expect that arm swing improves jumping height, which based on previous research will vary between 12–38% (Feltner et al., 1999; Hara, Shibayama, Arakawa, et al., 2008; Lees et al., 2004; Mosier et al., 2017, 2019; Vanrenterghem et al., 2008). To investigate in detail, we divided the arm swing into multiple phases according to the acceleration and deceleration of the swinging movement. We assume that the negative acceleration of the arm center of gravity induces an increased load on the lower extremities (higher GRF), which elevates muscle tension (greater EMG during SJAS and CMJAS) and may lead to an increased force output and consequently to a greater jump height (Hara, Shibayama, Takeshita, et al., 2008).

According to our knowledge no previous study has investigated the temporal characteristics of the EMG signal and has compared kinetic and kinematic variables with time resolution. Such data can provide more detailed information about how arm swing influences the vertical ground reaction force, lower limb extensor muscles EMG activity and joint angle displacement over time.

METHODS

Sixteen physically active men volunteered to participate in this study (mean±SD age 22.9±3.3 years, body height 1.8±0.7 m, and body mass 77.6±10 kg). The participants were physical education teacher students. Participants had no musculoskeletal injury or pain in the lower and upper extremities. All participants were informed of the type, the nature and the risks of the measurements prior to the experiment and they signed a written informed consent to take part in the study, which was performed in accordance with the Declaration of Helsinki and was approved by the ethics committee of the Hungarian University of Sports Science (TE-KEB/09/2022).

PROTOCOL

The procedure consisted of a single testing day. Before testing, participants performed a standardized warm-up protocol consisting of five minutes riding on a bicycle ergometer, dynamic stretching of the thigh and hip muscles and submaximal vertical jumps. Surface EMG electrodes and reflective markers were attached to the right lower leg (Figure 1). Then, three SJ akimbo and three SJAS were performed. In SJAS, participants were asked to extend their arms backward and hold them in that position prior to the jump. SJ was executed from a stationary, semi-squatting position (90° knee joint). The jumping movement and the arm swing initiation were performed at a self-preferred timing. For SJ and CMJ without arm swing, participants were asked to keep their hands on their iliac crests throughout the whole jump. Next, three CMJ and three CMJAS were executed. Participants were instructed to execute each jump with maximum effort. Immediately after the end of the backward arm swing jump movement begins with a quick forward and upward arm swing and an explosive extension of the legs. Arm swing stopped when the hands reached the height of the face. Therefore, the upper arm was in a locked position when the maximum height of the jump was achieved. During the jumps the researchers visually monitored each attempt. At least three-minute rest was provided for the participants between trials while the trial data were saved. Leg joint kinematics and leg muscles electrical activity were recorded simultaneously during the jumps. We used a custom-built synchronization module to synchronize the kinematic, kinetic and EMG recordings.

GROUND REACTION FORCE DATA COLLECTION AND ANALYSIS

Participants performed the jumps on a force plate (Kistler Force Platform System 92–81B, Switzerland, sampling rate 1000 Hz) to obtain ground reaction force (GRF) data. The raw GRF time data were exported and processed in a custom written Matlab code (MathWorks Inc., Natick, MA, USA). A fourth-order low-pass Butterworth digital filter with a cutoff frequency of 50 Hz was applied to filter the raw GRF data (Barker et al., 2017). Based on the smoothed vertical GRF data the mechanical variables were calculated and presented in Tables 1 and 2. Jump and flight times were determined from the force-time curve.

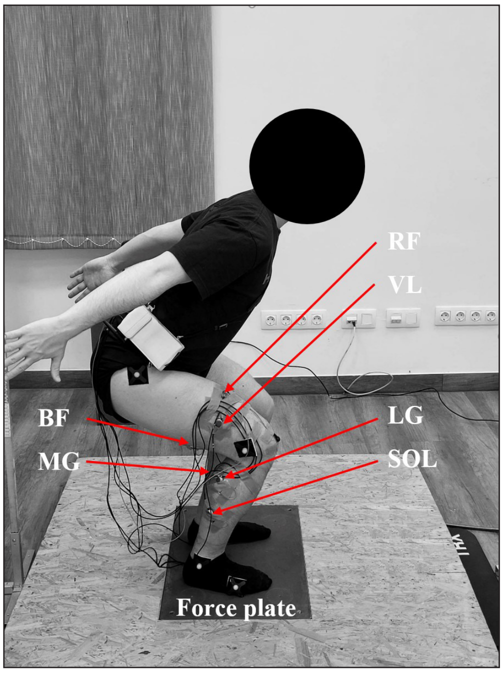

Figure 1 Experimental setup.

Location of the EMG electrodes and reflective markers on the right leg. Abbreviations: RF – rectus femoris, VL – vastus lateralis, BF – biceps femoris, MG – medial gastrocnemius, LG – lateral gastrocnemius, SOL – soleus.

VARIABLES	SJ MEAN ± SD	*p* VALUE	SJ AS MEAN ± SD
GRF peak (N)	1873 ± 343	0.00*	2065 ± 343
GRF norm (N/kg)	2.46 ± 0.30	0.00*	2.70 ± 0.33
GRF mean (N)	1342 ± 221	0.32	1376 ± 202
Net impulse (Ns)	757 ± 246	0.027*	827 ± 216
Kinetic energy (J)	232 ± 65	0.00*	310 ± 77
Flight time (sec)	0.48 ± 0.05	0.00*	0.54 ± 0.05
Jump time (sec)	0.32 ± 0.06	0.01*	0.36 ± 0.08
Jump height (m)	0.30 ± 0.07	0.00*	0.40 ± 0.09
Takeoff velocity ($m \cdot s^{-1}$)	2.42 ± 0.29	0.00*	2.80 ± 0.31
RSI mod ($m \cdot s^{-1}$)	0.96 ± 0.26	0.00*	1.17 ± 0.39
Power max (W)	3365 ± 1013	0.21	3239 ± 721
Mean power (W)	866 ± 464	0.00*	1320 ± 393

Table 1 Descriptive results (mean ± SD) for force related variables during squat jump. SJ = squat jump without arm swing; SJAS = squat jump with arm swing; GRF = ground reaction force; GRF norm = peak ground reaction force normalized to body mass; RSI mod = modified reactive strength index; *= $p < 0.05$ between SJ and SJAS.

VARIABLES	CMJ MEAN ± SD	*p* VALUE	CMJ AS MEAN ± SD
GRF peak (N)	1932 ± 294	0.76	1903.34 ± 294
GRF norm (N/kg)	2.59 ± 0.25	0.60	2.54 ± 0.21
GRF mean (N)	1522 ± 247	0.09	1461 ± 237
Net impulse (Ns)	218 ± 75	>0.00*	270 ± 70
Concentric time (sec)	0.27 ± 0.03	>0.00*	0.31 ± 0.03
Eccentric time (sec)	0.29 ± 0.03	0.09	0.34 ± 0.08
Flight time (sec)	0.53 ± 0.05	0.07	0.57 ± 0.06
Jump time (sec)	0.76 ± 0.14	0.04*	0.88 ± 0.14
Jump height (m)	0.37 ± 0.07	0.03*	0.44 ± 0.09
Takeoff velocity ($m \cdot s^{-1}$)	2.69 ± 0.27	>0.00*	2.94 ± 0.31
RSI mod ($m \cdot s^{-1}$)	0.50 ± 0.10	0.66	0.52 ± 0.15
Power max (W)	3465 ± 706	0.84	3422 ± 746
Mean concentric power (W)	1527 ± 246	0.57	1477 ± 245
Mean eccentric power (W)	943 ± 158	0.27	894 ± 132

Table 2 Descriptive results (mean ± SD) for force related variables during countermovement jump CMJ = countermovement jump without arm swing; CMJAS = countermovement jump with arm swing; GRF = ground reaction force; GRF norm = peak ground reaction force normalized to body mass; RSI mod = modified reactive strength index; *= $p < 0.05$ between CMJ and CMJAS.

KINEMATICS DATA COLLECTION AND ANALYSIS

The jumps were videotaped (120 Hz) by a digital camera to estimate hip, knee and ankle angular displacements. The camera was placed four meters from the force platform perpendicular to the sagittal plane of the participant and secured on a one-meter height tripod. Six retroreflective markers (1.5 cm diameter) were placed on the skin of the right side of the participants: (1) on the neck (on the vertical line of the auris externa at the height of the prominentia laryngea),

(2) on the hip (greater trochanter of the hip), (3) on the knee (lateral condyle of the femur), (4) on the ankle (lateral malleolus), (5) on the foot (5^{th} metatarsal head of the foot), and (6) on the wrist (5^{th} finger side – on the pisiform). Video analysis was performed in Kinovea (v. 0.9.5, http://www.kinovea.org/) to calculate hip, knee and ankle joint displacement and the velocity and acceleration of the arm in a sagittal plane. The marker locations were manually marked in each image. The neutral hip joint was considered 180 degrees when the longitudinal axis of the first and third marker was in line. The neutral knee joint was considered 180 degrees when the longitudinal axis of the thigh and shank was aligned. Neutral ankle joint (90 degrees) was defined when the shank was perpendicular to the foot base (sole). Hip, knee and ankle joint displacement was calculated from the angular displacement-time curve.

Arm swing was characterized by the movement of the marker placed on the wrist. Maximal positive and negative accelerations and the length of the positive and negative acceleration phases were determined based on the time – acceleration curve. Velocity and acceleration data was normalized to the peak velocity and peak acceleration.

ELECTROMYOGRAPHY

EMG activity of the investigated lower limb muscles was recorded during jumping with a Noraxon EMG system (TeleMyo, Noraxon U.S. Inc., Scottsdale, Az, USA) with a sampling frequency of 1000 Hz. Before mounting the EMG electrodes on the surface, skin preparation was performed (shaved, abraded lightly, and cleaned with alcohol). Silver-silver chloride bipolar surface electrodes (Blue Sensor M-00-S/25, Ambu, Denmark) with a 10 mm diameter and an inter-electrode distance of 20 mm (center-to-center) were placed on the medial gastrocnemius (MG), lateral gastrocnemius (LG), soleus (SOL), vastus lateralis (VL), rectus femoris (RF) and biceps femoris long head (BF) muscles. Electrodes were aligned parallel with the fascicle orientation and were placed following the SENIAM guidelines (Hermens et al., 2000) to minimize cross-talk between the muscles. The electrodes locations were adjusted by using ultrasonography as described elsewhere (Kovács et al., 2021). The reference electrode was placed on the ipsilateral patella. All EMG cables were taped over the skin to minimize movement artefacts. The raw EMG signals were band-pass filtered (20–450 Hz) with a fourth order zero-lag Butterworth filter to remove movement artefacts and signal noise. To quantify the surface EMG amplitude during jumps the root mean square (RMS) amplitude was calculated. To account for the time difference between the different execution times in jumps with and without arm swing we adjusted the RMS window size so the respective bandwidth can be the same in jump execution time (Mark Burden et al., 2014). For jumps with arm swing a 50 ms RMS window was used. Then, according to the shortening of the jump time in jumps without arm swing, the RMS window was reduced proportionately.

STATISTICAL ANALYSIS

The normality of each dataset was checked with Shapiro–Wilk's test to confirm the normal distribution of the data. The discrete variables calculated from the force-time data for each condition were compared with paired t-test. To compare the time normalized ground reaction force, joint angular displacement and EMG amplitudes we applied SPM analysis in Matlab using the open-source spm1d code (SPM M.0.4.8 www.spm1d.org). SPM two-tailed paired t-tests were used to compare time-normalized variables between jumps with and without arm swing. Detailed description of SPM can be seen elsewhere (Pataky, Robinson, et al., 2016; Pataky, Vanrenterghem, et al., 2016). The alpha level was set at $p \leq 0.05$.

RESULTS

Squat jump performed with arm swing increased the jump time and the flight time resulting in a 33% higher jump height (Table 1). The peak ground reaction force (GRF) and the mean mechanical power were significantly larger during SJ with arm swing than without arm swing. This difference for SJAS was observed mostly during the late push-off phase (71–91%, $p < 0.001$) (Figure 2).

Total jump time also increased for the CMJ with arm swing compared to CMJ without arm swing (Table 2). There was no difference in peak or mean GRF between CMJ and CMJAS, but jump time was longer, resulting in larger net impulse and consequently higher jump height by 18.9% when using arm swing. GRF was larger at CMJAS during the braking phase (15–24%, $p < 0.001$) and during the late push-off phase (89–97%, $p < 0.001$), whereas GRF was larger in CMJ without arm swing during the early push-off phase (64–82%, $p < 0.001$) (Figure 3).

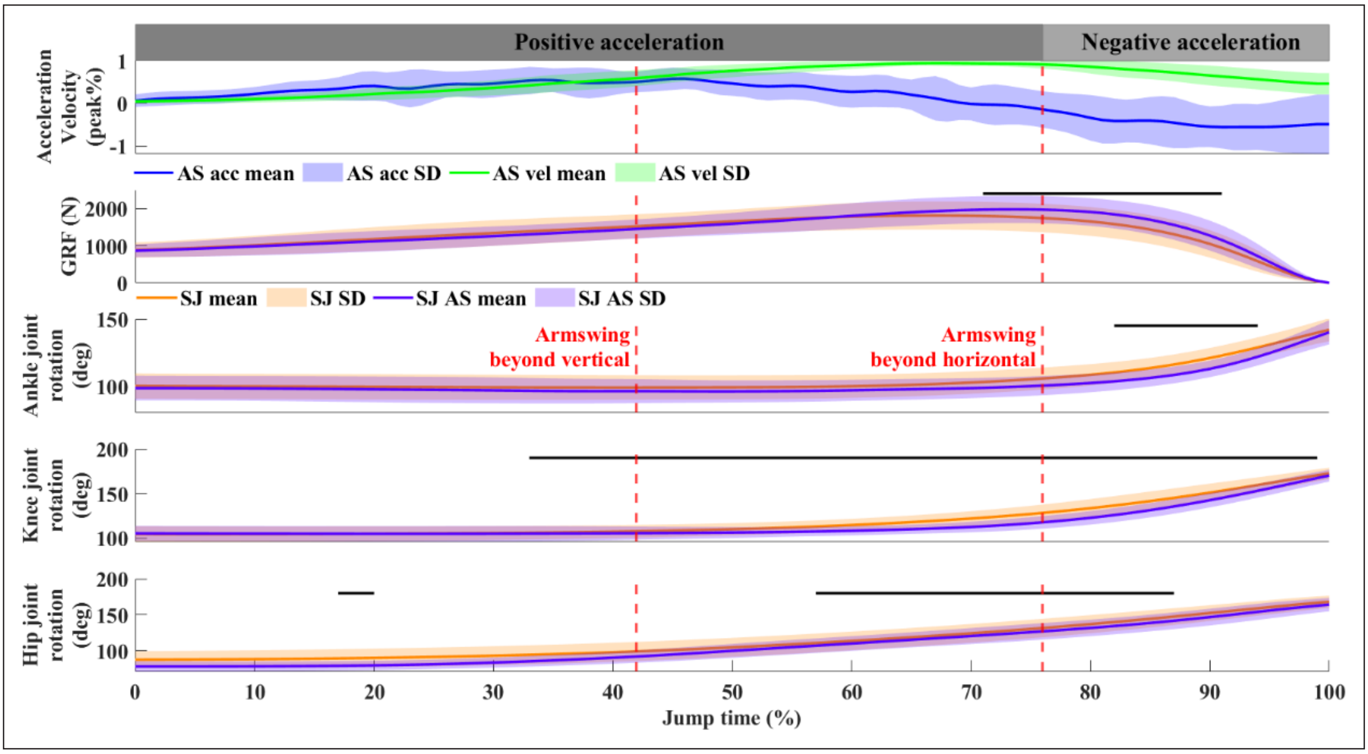

Figure 2 Time normalized kinetic and kinematic curves for squat jump.

The first panel represents the acceleration (blue line) of the arm swing normalized to the peak acceleration and the velocity (green line) of the arm swing normalized to the peak velocity during squat jump. The second panel shows the time normalized mean ground reaction force (GRF) during squat jump with (purple line) and without arm swing (red line). The lower panels show joint displacement of the ankle (solid line), knee (dash dot line) and hip (dotted line) during squat jump with (red line) and without arm swing (purple line). The solid line represents the average values of the group, whereas the shaded areas represent the standard deviation of the corresponding mean values. The first vertical line indicates the maximal positive acceleration of the arm swing, and the second vertical line shows the instant when the velocity of the arm swing is the highest (0 acceleration).

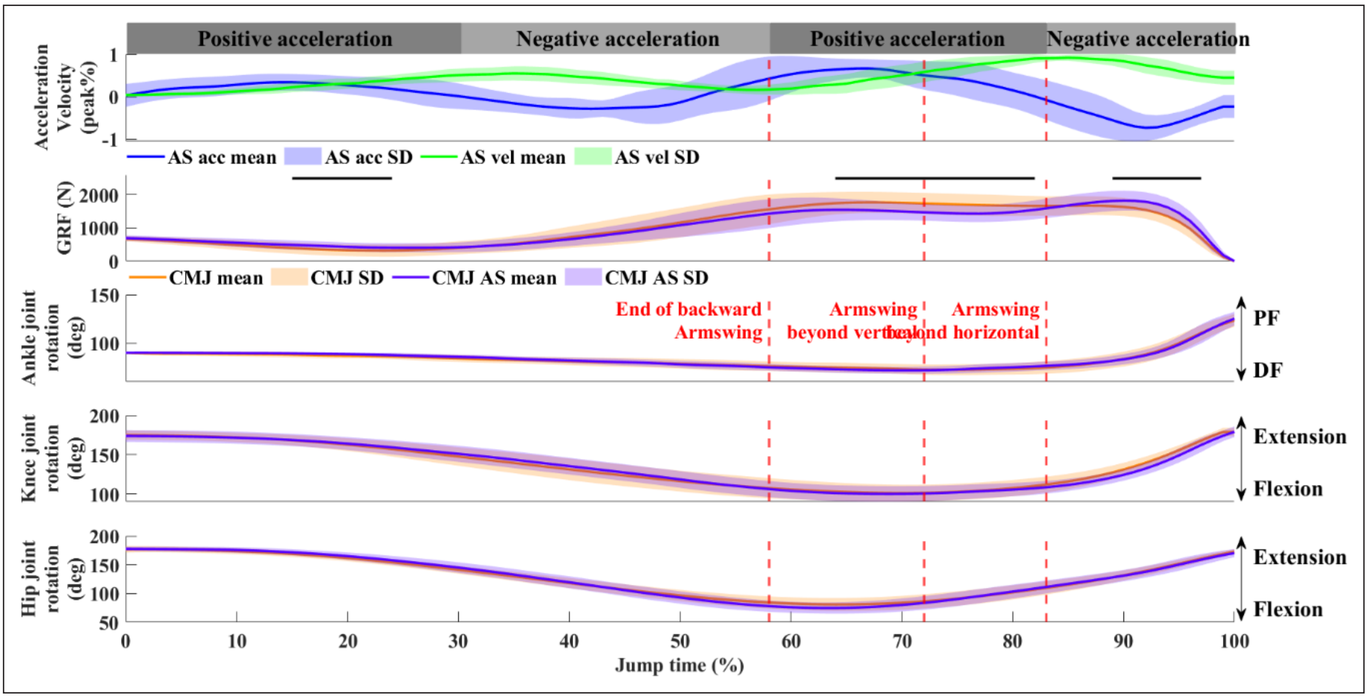

Figure 3 Time normalized kinetic and kinematic curves for countermovement jump.

The first panel represents the acceleration (blue line) of the arm swing normalized to the peak acceleration and the velocity (green line) of the arm swing normalized to the peak velocity during countermovement jump. The second panel shows the time normalized mean ground reaction force (GRF) during squat jump with (purple line) and without arm swing (red line). The lower panels show joint displacement of the ankle (PF = plantarflexion, DF = dorsal flexion), knee and hip during squat jump with (red line) and without arm swing (purple line). The solid line represents the average values of the group, whereas the shaded areas represent the standard deviation of the corresponding mean values. The first red vertical dashed line indicates the end of the backward swing. The second red vertical dashed line indicates the maximal positive acceleration of the arm swing, and the third line shows the instant when the acceleration of the arm swing goes beyond zero.

Figure 4 presents the EMG activity for squat jump (left panel) and countermovement jump (right panel). EMG signal was quite similar between jumps with and without arm swing during both SJ and CMJ. Differences were found for a short period during SJ for VL with higher muscle activation in jump without arm swing at the early push off (0–14%, p = 0.014). BF showed higher EMG activity during backward arm swing (23–26%, p = 0.01) in SJAS, while MG (56–58%, p = 0.018) and SOL (52–55%, p = 0.02) showed higher EMG activity at mid jump time during SJ. The EMG signal of the RF showed no difference between jump conditions. CMJAS resulted in higher VL (38–56%, p = 0.02) and RF (47%, p = 0.014) EMG activity at the braking phase. LG demonstrated higher EMG activity during CMJAS at several short periods of the first braking phase of the jump as well as SOL (Figure 4).

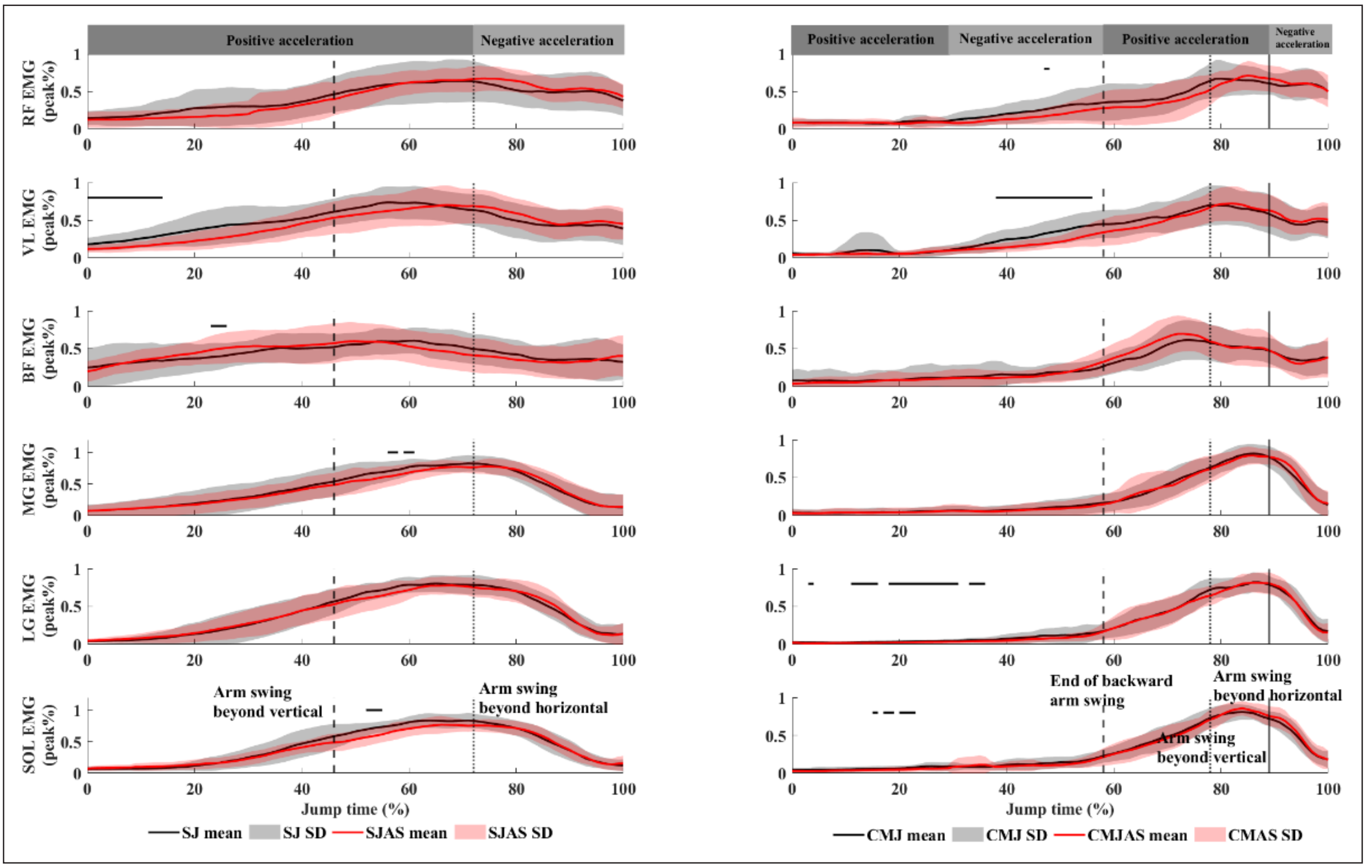

Figure 4 Time normalized myoelectrical activity curves.

Left panel: squat jump without (SJ) and with arm swing (SJAS), right panel: countermovement jumps without (CMJ) and with arm swing (CMJAS). Solid lines represent mean values, whereas the shaded areas the standard deviation. Comparison between jumps with arm swing and without arm swing was calculated via spm statistics. Where the curves are significantly different from each other a horizontal black solid line was drawn. Red dashed vertical line shows the notable timestamps of the arm swing as the first peak positive acceleration, first negative peak acceleration and second peak positive acceleration.

There was a significant difference in ankle joint angular displacement between SJ and SJAS at the late push off phase (82–94%, p = 0.036). Knee extension was significantly lower in SJ compared to SJAS from 33–100% ($p < 0.01$) of the jump time. Hip extension was also smaller at 17–20% (p = 0.048) and 57–87% (p = 0.001) of the jump time in SJ than SJAS. CMJ and CMJAS showed similar kinematic characteristics.

DISCUSSION

This study aimed to examine the effects of arm swing on the mechanical characteristics and the EMG activity during vertical jumping in relation to the kinematic changes of arm swing. The main finding was that arm swing increased jump height, but without a concomitant increase in muscle activation of the lower limb.

SQUAT JUMP

In squat jump with an arm swing, the higher jump height can be explained with the increase in both force related and time related variables, which resulted in larger net impulse and in turn higher takeoff velocity. This larger GRF during SJAS was measured in the late push off phase of the jump when the arm swing had the highest negative acceleration. This finding is in alignment with the “pulling theory” as described in earlier studies (Harman et al., 1990) and confirms our initial assumption that arm swing’s negative acceleration generates additional load on the lower limbs increasing the force acting on the ground. However, the EMG data did not confirm increased

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muscle tension, therefore, we cannot demonstrate directly that higher load on the lower limbs induced by arm swing is paired with higher muscle tension. Despite some minor differences in EMG signal, muscle activation in our study can be considered similar during SJ and SJAS.

Performing SJ with arm swing resulted in a longer jump time, which indicates different temporal characteristics of the lower limb's joints extension compared to SJ, especially in the knee joint. Because the starting and take off positions were almost identical, this difference can be explained by the shorter duration when performing the jump without arm swing, thus the similar magnitude of joint angular displacement may occur quicker in SJ than is SJAS.

Most probably, arm swing changed the kinematic characteristics of the jump by delaying the initiation of the joints extension while keeping the duration of extending the ankle, knee, and hip joints and the extension velocity similar, particularly during the first half of the push off. Further, at the late push off phase, GRF was significantly larger in SJAS indicating higher acceleration of the center of body mass which can be achieved with quicker joint extension, thus the velocity of the joint extension most likely was higher during this phase.

Feltner et. al. (1999) have proposed that the slower joint extension induced by arm swing enables the extensor muscles to increase force output. Similarly to our results, Hara et al. (2008) found longer jump time in SJAS with higher ankle and hip joint work possibly because of the longer muscle contraction time, which is beneficial for higher force output. In the case of larger force output in jumps with arm swing we should detect higher muscle tension through higher EMG activity in the leg extensor muscles during the push-off phase, but this was not confirmed by our results. A possible explanation for these findings is that EMG measurements measure muscle activity at a single area of the muscle, which may not be enough to detect considerable changes in muscle tension. Larger force output is most likely the result of the synergetic action of the whole muscle. Perhaps, a multichannel EMG could give a more comprehensive insight of the electromyographic activity in various areas of the muscle. The results also show that after the initiation of arm swing, the lower limb joints delayed to extend until arm swing reached the vertical line, which resulted in increasing jump time. It is possible that by extending the joints before arm swing reaches the vertical position could be counterproductive, because the acceleration of the arm's and consequently of the whole body's center of mass is directing towards the ground.

COUNTERMOVEMENT JUMP

As expected, CMJAS resulted in greater jumping height compared to CMJ. Although, the peak or mean GRF was not different between jumps with and without arm swing, jump time was considerably longer in CMJAS than in CMJ. Since a similar magnitude of force was applied for a longer duration a larger net impulse was achieved resulting in greater jump height.

In CMJ, changes in force-time curve can be divided into three phases according to arm swing kinematics. More specifically, to backward swing, to forward swing until the vertical position, and to forward swing from the vertical to beyond horizontal position. The deceleration (negative acceleration) of the backward arm swing during the mid-descending phase of the jump induced an elevated GRF for a short duration, which likely increased the load on the lower leg and the subsequent residual force. This in turn can increase the activation of the muscles during lengthening. Similarly, to squat jump, larger muscle activation during the CMJAS was not paired with higher EMG amplitude in VL and RF muscles during the braking phase. It seems that the active muscle fiber lengthening during the downward phase in CMJAS only evoked a relatively slow stretch followed by a short "quasi" isometric phase, when the backward arm swing ended and started to move forward. The delay between the end of active lengthening (braking) and the subsequent concentric contraction (push off) is relatively long and it likely reduced the effects of residual force enhancement (Bobbert et al., 1996).

During forward arm swing, when the arms accelerated towards the vertical position, GRF was lower than in CMJ. During this phase, the arm accelerates to the direction of the gravitational force while the ankle, knee and hip joints' extension has not yet started, thus the whole body's acceleration toward the ground increases which can explain the lower vertical GRF.

After the arms passed the vertical line, the arm swing started to decelerate and the negative acceleration was the highest beyond the horizontal line. In this phase larger vertical GRF was observed which indicates an elevated force output. According to the "pulling theory" (Harman et al., 1990) in this phase the upward pulling effect of the arms should increase the load on the lower leg also increasing the GRF. Our initial hypothesis was that the negative acceleration increases the load on the lower limb muscles, which was confirmed by the higher vertical GRF during the peak negative acceleration. However, similarly to SJAS, there was no difference in muscle EMG activation pattern between CMJ and CMJAS, thus we cannot confirm that the negative acceleration of the arm swing increases muscle tension (i.e., higher EMG activity) in the lower limb despite having larger GRF.

In oppose to the findings in SJ, there was no difference in ankle knee and hip joint rotation between CMJ and CMJAS, which indicates that the joints flexion and extension occurred in a relatively similar manner. However, it must be noted that the angle-time curves were compared after time normalization, and the absolute jump duration of CMJAS was significantly longer meaning that joint flexion and extension time was also longer. From this, we can assume that under similar joint extension, muscle contraction was longer which may allow the muscles to work on a more favorable region of the force-velocity curve as slower contraction velocity pairs with higher contraction force (Domire & Challis, 2010). Although, we cannot confirm this assumption since we did not find higher EMG activity (possibly greater muscle force) during the push off phase in CMJAS.

The applied methodology used in this study have some limitations which need to be addressed. Ankle, knee, hip and shoulder joint work and torque were not calculated in this study, which could provide greater insight how arm swing affects lower limb muscle function. To characterize arm swing we used the velocity and acceleration of the marker placed on the wrist which may not represent well enough arm swing characteristics. Moreover, the limited size of the sample raises some concern about generalizing the conclusion. To account for sample size, we calculated a post-hoc power based on our results, which showed 95% statistical power for SJ which is considered very high and 89% statistical power for CMJ which is also well above the generally accepted 80%. Bipolar EMG electrodes only pick up signals from a limited area of the muscle, but muscles are known to have regional activation patterns (Gallina et al., 2022) thus the applied method in this study may not be accurate enough to detect changes or represent sufficiently muscle activation during vertical jumps performed with and without arm swing.

CONCLUSION

This study focused on the presumed increased load on lower limb muscles induced by the negative acceleration of the arm swing. Our results demonstrate that arm swing significantly increases jump height in both SJ and CMJ. Jumps performed with arm swing resulted in higher GRF during the late push off phase (at peak negative acceleration of the arm) only in SJ, but not in CMJ. Larger GRF suggests higher load on the lower limb, however, there was no increase in the extensor muscles' EMG activity. Therefore, we can conclude that arm swing induces changes in the temporal characteristics (extended jump time) favoring the mechanical components of the jumps, but without a significant increase in EMG activity.

COMPETING INTERESTS

The authors have no competing interests to declare.

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