Upper-limb motion and drop jump: effect of expertise

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Aim. In this study, the role of arm motion in a drop jump was investigated in skilled and unskilled subjects.
Methods. Nine skilled volleyball players and 8 novice individuals performed a series of jumps from two different heights: 30 cm and 60 cm. Free and restricted arm motion were used to determine the effect of arm motion on the vertical jump. Participants were instructed to land on a force plate and jump as high as possible. The ground reaction force was measured with an AMTI force plate (500 Hz). The kinematics of the jumps was recorded with two digital cameras (50 Hz).
Results. The motion of the arms during the jumps was found to increase the jump height by 15% for the volleyball players and 12% for unskilled jumpers. Volleyball players performed better in the 60 cm than in 30 cm drop height (+8.5%). In the volleyball players, the peak vertical ground reaction force during take-off increased by 7%, the peak power increased by 10.6% while the peak impact force decreased by 6.3%.
Conclusion. Skilled jumpers were found to have a better use of arm motion than novices in (i) increasing the vertical jump performance, (ii) controlling the balance of the body at take-off (iii) leaving the ground with an optimal body orientation.

KEY WORDS: Volleyball - Force pattern - Kinetics - Kinematics.

Maximizing the height of a jump involves a complex movement sequence requiring the precise coordination of all body segments. In this coordination pattern, the upper limbs seem to play a crucial role in increasing the vertical elevation during the flight phase.[1-5]

Over the past years, research has focussed on the role of upper-limb movement on the one-leg vertical jump and the standing vertical jump but not in the drop jump. In the one-leg vertical jump, such as in high jumping,[6-10] upper-limb motion contributes to the increase in maximum vertical ground reaction force,[1] and the coordination between upper and lower-limb motion has a crucial effect on jumping performance. The impulse time is primarily influenced by the quality of this coordination.[9] The arm motion appears to be different according to the level of expertise. Novices flex the upper-limbs throughout the whole take-off phase. Experts accelerate the upper limbs (velocity of the forearm) during the preparatory counter movement from 4 m/s to 12 m/s and hold them still at take-off.[1] The optimum arm/forearm angle of fixation at take-off is about 90°.[7, 8] An incorrect timing between arm and leg movements increases the duration of the eccentric phase.[9] However, the way the arms are used during

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the jump has several consequences on leg lowering. In the high jump, Ae et al.[6] have shown that the use of both arms in the run to jump transition increases the maximum knee flexion (mean value: 110°), the maximum ankle flexion (about 60°), and the impulse time [10] (240 ms). With single arm motion, where only the arm opposite to the jumping leg is used, the maximum flexion of the knee is about 140°, the maximum ankle flexion is about 80°, and the impulse time is reduced to 160-180 ms.[10]

In the standing vertical jump, many studies have attempted to quantify and describe the gain in performance induced by arm motion.[3-5, 11, 12] Generally, arm motion increases by 10% the vertical take-off velocity,[3] which itself increases significantly the jumping height. The throw-and-fix technique performed with an optimum timing accounts for approximately 12% of the increase in efficiency [3] (take-off velocity) based on the increase in height and velocity of the body's center of mass at take-off as well as the increase in the maximum vertical ground reaction force.[3-5, 11, 12] In addition, arm motion reduces the touch-down impact force and decreases the vertical ground reaction force in passive peak, therefore reducing the risk of injuries.[5]

Another type of jump usually used to test or train the plyometric muscular features in many jumping sports such as basketball, volleyball and the Fosbury-flop is the drop jump. This jump implies dropping from a particular height, landing on the floor and then jumping vertically. To our knowledge, there are no studies available having quantified the role played by arm movements during the drop jump phase, and it is the aim of this contribution to assess such a role.

Three questions need to be addressed in order to understand the role played by the arms during the drop jump:

a) Is arm motion used to increase the vertical jumping performance, as reported in other types of jumps (single-legged running jump, standing vertical jump)? In this case, which mechanical parameters are responsible for the gain in performance?

b) What is the contribution of the arms to the general behavior of the jumper? We assume that arm motion is also used to control the high moment and the high passive peak of the vertical ground reaction force resulting from the landing phase,[10] considering the high level of mechanical constraints occurring when landing from an important dropping height.

c) Have experts a better utilization of arm motion than novices during jumping? We hypothesized here that arm movements in experts reflect a stable and efficient (increasing the vertical velocity) coordination, resembling the throw-and-fix technique reported in the other types of jumps (e.g. Dapena,[7, 8] in Fosbury-flop).

Materials and methods

Subjects

Eight unskilled adult males with a mean height of 1.78 m (SD 0.06 m), a mean mass of 76 kg (SD 7.6 kg), and a mean age of 22.6 y (SD 4.6 y), and 9 skilled volleyball players (in the 3rd French division) with a mean height of 1.84 m (SD 0.07 m), a mean mass of 80.1 kg (SD 8.5 kg), and a mean age of 23.2 y (SD 5.4 y), performed a series of drop jumps. A Student's t-test has been calculated in order to show the homogeneity of the initial variables: no significant difference existed between the two groups for body mass [$T(15)<1$], and height [$T(15)=2.17$; $P>0.05$]. All participants consented to participate in the experiment on a voluntary basis and were treated in accordance with the ethical principles of human research experiments as provided by the University of Paris XI.

Test protocol

Before the beginning of the experimental session, each participant was instructed to warm up for a few minutes by running, stretching and jumping. All subjects were in good physical condition and had no injuries or disabilities. Each subject performed 8 drop jumps with free arm movements (DJFA) and 8 drop jumps with restricted arm movements (DJRA) at a 30 cm drop jump height (DJ30) or at a 60 cm drop jump height (DJ60). For DJRA, participants were instructed to keep the hands on their hips. The level of the drop jump was set using one box DJ30 or two boxes DJ60. Trials were presented in a randomized order and counterbalanced between participants, in order to avoid order effects. Each experimental session lasted about 30 min, including a 1-min rest every 4 trials and about 30 s between each jump. Subjects stood on the box in all modes (DJRA or DJFA) and dropped on the force plate at a "Go" signal. They were instructed to jump as high as they could (Figure 1).

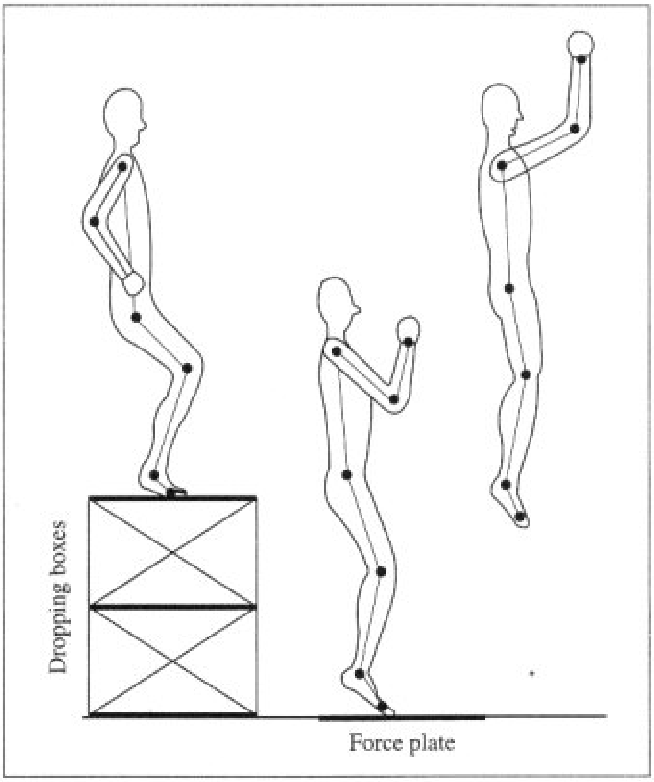

Figure 1.—Experimental task: participants were standing on one or two boxes (30 cm or 60 cm), dropping down onto the force plate at a "Go" signal, and jumping as high as they could with the arms free to move (such as in the figure) or fixed on the hips.

Kinematic analysis

A video-based kinematic recording system (50 Hz) was used to study the general behavior of the subjects during the jump at crucial moments in time: landing, maximum shortening, take-off and apex of the jump. Eight passive reflective markers were attached to the skin (or shoe) of each subject and on the left side of the body: ball of the foot, lateral malleolus (ankle joint), lateral tibial plateau (knee joint), greater trochanter (hip joint), acromonion process (shoulder joint), lateral epicondyle of the humerus (elbow joint), styloid process of the ulna (wrist joint) and 7th cervical vertebra. The motion of these markers was recorded via two JVC DVX-400EG marks video cameras at a frequency of 25 Hz. The highest possible resolution 1 024×768 pixels was used. The data acquisition region was calibrated to 2 m wide × 1 m deep and 2.8 m high using the standard procedure recommended by the constructor of the video cameras: a rectangular frame constructed of metal pipe to which 14 reflective markers were attached at prescribed locations. These markers served as the calibration points in analysis. The average mean error associated with absolute point reconstruction was <1 mm (SD 0.1 mm) along axis X, Y, Z. For the angular accuracy it was found that for 1° to 240° the mean of the average deviations is about 0.14° (SD 0.06°). Synchronization between the two cameras was achieved with an infrared remote control. This procedure has no influence on the accuracy of measurement. Video frames were split into separate fields in order to achieve 50 pictures per second. The calibrated volume was 2 m × 1.5 m × 3 m (length x breadth x height). The two cameras were used to perform a mono-lateral 3D kinematics analysis. Kinematic position data were smoothed using a fourth-order low-pass Butterworth filter with a cut-off frequency of 10 Hz.

Video data treatment

The video images were captured with a pinnacle studio DV8 card. They were semi-manually digitized, frame-by-frame, with appropriate customized software. Frames were recorded and saved on a computer with the ULEAD Video Studio software. The video cameras and the AMTI force plates where synchronized using external electrical timer.

Kinetic data were recorded with a 40 cm × 40 cm AMTI OR 6-5 force plate, sampled at a frequency of 500 Hz. The vertical velocity of the center of mass was obtained by integrating the vertical ground reaction force (VGRF). The initial velocity of the center of mass at touch-down was estimated by using the potential energy method,[13, 14] using: $v = (-2g \times h_{drop})^{1/2}$ where g is the acceleration due to gravity and h_{drop} the initial height of the drop box. Assuming that the initial position of the center of mass of some subjects falling from the drop box could differ from the real height, we used a corrected fly-time method to evaluate the height of the fall with more accuracy.[13] Fly time has been estimated by calculating the number of frames during the drop. The co-ordinates of the markers were combined with the data from Clauser et al.[14] in order to obtain the position of the center of mass of the whole body by assuming a symmetric geometry. The displacement of the center of mass was calculated from the double integration of the acceleration data.[15-17] The CM position is of importance in order to calculate the moments. To calculate the absolute position data,

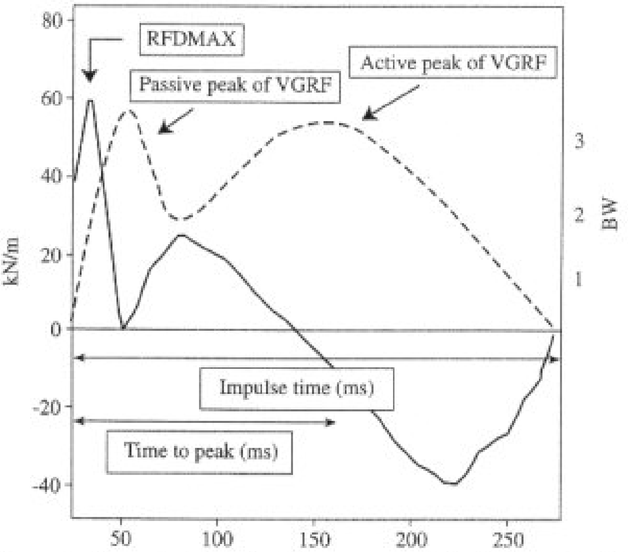

Figure 2.—Example of a typical force curve scaled to body weight (dotted line) with active and passive peak of the vertical ground reaction force (VGRF), impulse time (IT), time to peak (TTP) and rate of force development (RFD) at impulse for drop jump (continuous line).

the position of the center of mass at a certain point in time was required. The height of the subject's body center of mass at initial contact was defined as zero.[18] The rate of force development (RFD) was obtained by calculating the first time derivative of the vertical ground reaction force. The GRF data were filtered with a low pass filter (10 Hz cut off frequency). The mechanical power was obtained by multiplying the vertical ground reaction force by the vertical velocity during the impulse time and was normalized to body weight. The jump performance was calculated from the flight time according to Komi et al.[19] by using: $h = (g \times t^2)/2$ where t is equivalent to $^1/_2$ flight time and g is the acceleration due to gravity. This fly time method is known to overestimate the jumping height as compared to high-speed cinematography, with errors less than 3%.[19, 20] Only the jumps correctly executed were analyzed, i.e. only jumps where the values of the integral of the horizontal GRF components approximated zero.

The impulse was obtained by integrating VGRF over the contact period with the ground (Figure 2).

In addition, a spring-mass model, consisting of a mass attached to a single linear mass-less spring, was used to analyze the mechanics of the jump.[21-23] We considered leg stiffness as a general mechanical concept that captures the global behavior of the body during the jump. During the contact phase, leg length r was defined as the distance between the body center of mass and the ball of the foot, considered as the rotational center of the system during ground contact. Leg stiffness was defined as the ratio of the maximal ground reaction force Fmax during the active peak to the leg shortening (r at the time of maximum leg shortening namely:[22]

$$k_{leg} = Fmax/\Delta rmax \qquad \text{(Equation 1).}$$

Statistical analysis

A repeated-measures analysis of variance (F for ANOVA) was used to test the effect for expertise (between subject factor), arm motion (within factor), and drop height (within subject factor) on the biomechanical parameters of the jump (with $P<0.05$).

Results

Vertical jump performance

In general, participants jumped higher with free arm movements than with restricted arm movements ($F_{1,15}=13.99$; $P<0.05$): experts jumped 15% higher (50.3 cm, SD 5.1 cm) in DJFA than in DJRA (43 cm, SD 5.6), and novices jumped 12% higher in DJFA (43.2 cm, SD 6.2 cm) than in DJRA (37.7 cm, SD 6.9 cm), (Figure 3). There was no effect of height ($F<1$), but a significant effect of expertise ($F_{1,15}=23.84$; $P<0.05$), indicating that experts jumped higher (46.8 cm) than novices (40.35 cm).

The interaction between expertise and drop height was significant ($F_{1,15}=8.14$; $P<0.05$), suggesting that the initial height of the dropping location contributed more to the vertical performance for experts (increase from 45 cm to 49.24 cm) than for novices (decrease from 44.9 cm to 41.4 cm). No other interactions were found to reach significance.

Temporal parameters of the jump

All results are summarized in Figure 3 as well as in Tables I and II. Here we analyze the impulse time, the time to positive peak force and the impulse, defined as the integration of the vertical ground reaction force during the impulse time. The rate of maximum force development, providing information about the general shape of the force pattern, is also analyzed.

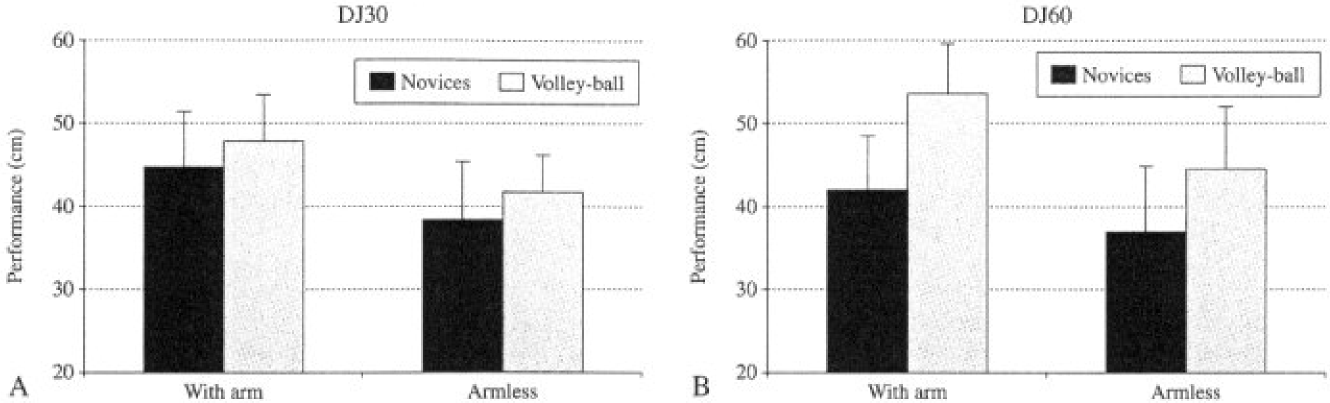

Figure 3.—Mean (+1 SD) performance in drop jumping from 30 cm (A) and 60 cm (B) in both experimental arm conditions (arms free or fixed) for experts (volley-ball players) and novices.

IMPULSE TIME

The dropping conditions changed the value of impulse time ($F_{1,15}$=4.83; P<0.05), with mean values of 384 ms in DJ30 and 406 ms in DJ60. The presence of arm motion did not change the impulse duration (392 ms in the free arm condition and 396 ms in the fixed arm condition). There was no effect of expertise on impulse time, with mean value of 384 ms for novices and 405 ms for experts. Finally, no interaction was found to exist between arm motion, drop height, and expertise (all Fs<1).

TIME TO PEAK FORCE

The motion of the arms did not change the time to peak force (TTP) (F<1), with a mean value of 200 ms in the free arm condition and 184 ms in the fixed arm condition. There was no effect of expertise (F<1), with a mean value of about 190 ms for both groups, and no effect of the dropping condition (1% to 4%; F<1). Interactions also failed to reach significance (all Fs<1).

IMPULSE

An ANOVA test revealed a significant main effect of the dropping height on impulse [$F_{1,15}$=6.89; P<0.05], showing that increasing the initial height of the drop jump changed the general shape of the force-time curve. Furthermore, the impulse value was greater for experts than for novices (+8% in DJ30; +13% in DJ60) ($F_{1,15}$=19.63; P<0.05), indicating two different motor strategies (Figure 4). Experts had a mean value of impulse of 790 N·s, and novices a mean value of 700 N(s (+12%). There was no interaction between the factors. The durations of the different tests was slightly different but a temporal normalization was not necessary.

RATE OF MAXIMUM FORCE DEVELOPMENT

The ANOVA test showed a significant main effect of the dropping conditions ($F_{1,15}$=54.43; P<0.05) on RFDMAX, showing that jumping from a higher position changed the shape of the force-time curve by increasing the passive peak (Figure 4). The dropping condition (DJ60) increased the value of RFDMAX by +43% (161 kN/s in DJ60 and 93 kN/s in DJ30). There was no significant main effect for arm motion on RFDMAX (F<1). The RFDMAX value was greater for novices (126 kN/s) than for experts (90 kN/s); ($F_{1,15}$=6.67; P<0.05). An interaction was found between expertise and dropping condition ($F_{1,15}$=11.91; P<0.05) indicating that RFDMAX increased in the DJ30 (+21% for experts, +6.7% for novices) but decreased in DJ60 (-13.3% for experts and -17% for novices). No other interaction was found to be significant (all Fs<1).

Force parameters of the jump

All results are summarized in Tables I and II. Here we analyze the classical force parameters: the maximum vertical ground reaction force at passive and active peaks, providing information about the landing impact shock and the subject maximal push, respectively, the relative peak of power, the negative and

TABLE I.—*Comparison of jumping parameters in DJFA and DJRA for novices and experts (volleyball players) in the 30 cm drop jump condition.*

	Volley-ball players			Novices		
	DJFA	DJRA	% difference	DJFA	DJRA	% difference
Vertical performance (cm)	47.7±5.7	41.8±4.2	12.2*	44.8±6.4	38.5±6.8	14.2*
Active peak VGRF (BW)	3.69±1.17	3.43±0.96	6.8	3.19±0.3	3.19±0.4	0
Passive peak VGRF (BW)	3.4±1.36	3.56±1.52	-4.7	3.28±0.59	3.29±0.73	-0.5
Power (W/kg)	106.7±21.9	88.3±20.6	17.2*	48.5±5.6	54.2±8.8	-10.7*
Impulse time (ms)	396±154	396±140	0.1	370±79	378±88	-2.2
Time to peak (ms)	218±131	185±78	14.9*	183±35	177±29	2.9
RFDMAX (kN/s)	110.9±46.7	87.6±46	21*	90±18	84.6±26.1	6.7
Peak +M (N·m)	76.2±28.7	75.7±21.8	0.7	48.8±19	54.7±10.4	-10.6
Peak -M (N·m)	-72.2±32.9	-65.4±19	9.4*	-59.1±23.2	-57.3±23	3.2
Leg stiffness (kN/m)	16.5±1.6	15.3±2.1	7.2	10.5±0.9	8.8±1.1	16.1*
Impulse (N/s)	736.5±220	753.8±166	-2	688±112	683±127	0.7

*P<0.05.

TABLE II.—*Comparison of jumping parameters in DJFA and DJRA for novices and experts (volleyball players) in the 60 cm drop jump condition.*

	Volley-ball players			Novices		
	DJFA	DJRA	% difference	DJFA	DJRA	% difference
Vertical performance (cm)	53.5±5.9	44.3±7.5	17.1*	44.6±6.4	36±7.6	19.2*
Active peak VGRF (BW)	3.78±1.48	3.52±1.19	6.9	3.24±0.24	3.0±0.24	8
Passive peak VGRF (BW)	4.34±1.16	4.68±1.66	-7.7	4.81±0.58	4.88±0.81	-1.3
Power (W/kg)	123.4±23	118.3±25.1	4.1	100.7±11.5	100.2±18.3	-0.5
Impulse time (ms)	416±168	415±151	0	386±70	409±66	-5.5
Time to peak (ms)	221.5±157	189±74	14.2*	178±19	187±34	-4.9
RFDMAX (kN/s)	147±56	167±54	-13.3*	150.3±46.4	181.8±55.7	-17*
Peak +M (N·m)	97.8±25	110.9±28.4	-13.4*	83.8±19	101±32.8	-17.3*
Peak -M (N·m)	-87±26.6	-100±28.6	-15.9*	-72.3±23	-64.5±38.4	12
Leg stiffness (kN/m)	16.7±1.9	13.3±2.3	20.3*	10.6±1.4	7.1±1.3	33*
Impulse (N/s)	849±218	820±183	3	724±101	755±104	-4

*P<0.05.

positive moments, providing information about balance and the leg stiffness (Figure 5).

ACTIVE PEAK VGRF

The contribution of the arms did not change the active peak of VGRF ($F_{1,15}$=1.48; P>0.05), as evidenced by similar values in the two conditions (3.48 times body weight(BW in the free arm condition and 3.29 BW in the fixed arm condition). The drop conditions induced small differences in the values of the active peaks of VGRF, that failed to reach significance (<1%, F<1). Experts showed higher values (+13%) than novices ($F_{1,15}$=8.75; P<0.05), suggesting a better maximum push-off phase. No interaction was found between arm motion, drop height, and expertise (all Fs<1).

PASSIVE PEAK VGRF

Drop height increased the passive peak of vertical force by +27.7%, from 3.39 BW in DJ30 to 4.69 BW in DJ60 ($F_{1,15}$=51.8; P<0.05). No other main effect was found on expertise and arm motion (F<1), showing closed values of the passive peak of VGRF: 3.96 BW in the free arm condition, 4.12 BW in the fixed arm condition, 4 BW for experts and 4.08 for novices. No interaction was found.

RELATIVE PEAK OF POWER

There was no main effect (F<1) of arm motion on the relative peak of power (mean value: 95 W/kg in the free arm condition and 91.9 W/kg in the fixed arm condi-

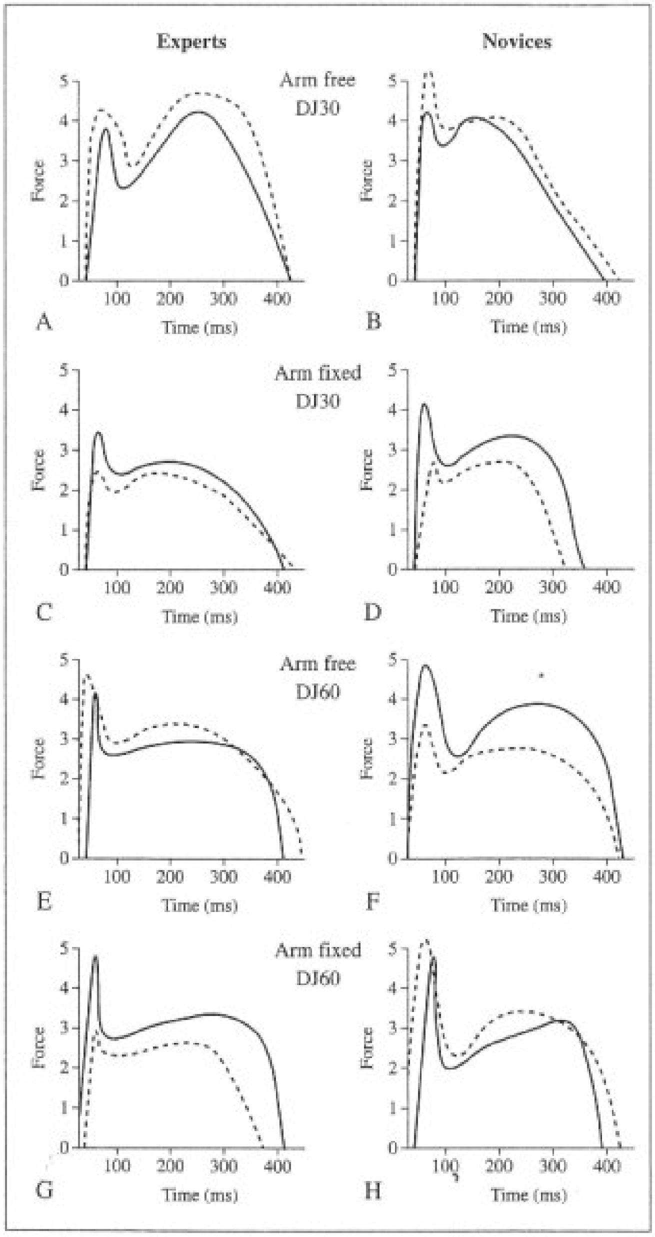

Figure 4.—A-H) Time histories of the ground reaction force scaled to body weight of two typical subjects in both arm conditions (arms free or fixed) for experts (volley-ball players, left) and novices (right).

tion). Experts showed higher values (109.6 W/kg) than novices (77.3 W/kg) ($F_{1,15}$= 12.25; P<0.05). Changing the initial height of the drop from DJ30 to DJ60 increased the relative peak of power by +33% ($F_{1,15}$=15.82; P<0.05), with a mean value of 111.9 W/kg in DJ60 and 75 W/kg in DJ 30. No interaction was found between arm motion, drop height, and expertise (all Fs<1).

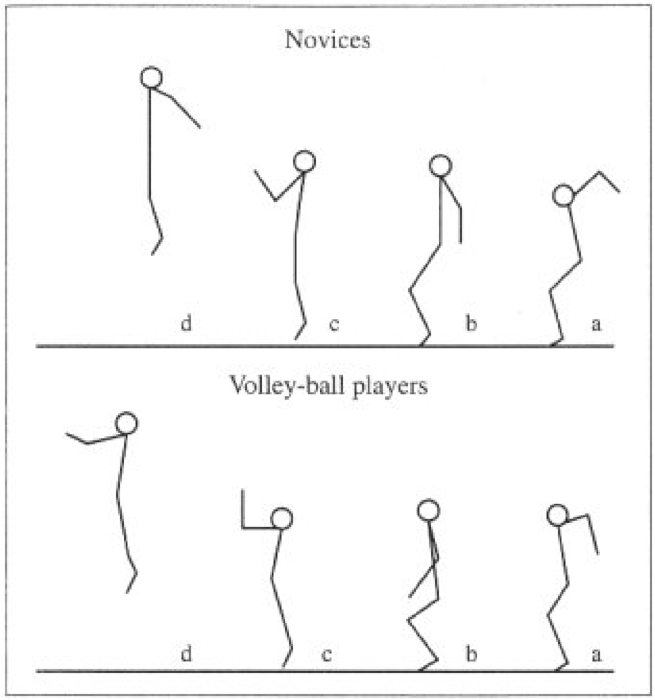

Figure 5.—Kinematics of drop jumps at 4 crucial moments (a) touch-down, (b) maximum shortening, (c) take-off and (d) apex of the jump for experts (volley-ball players) and novices.

Maximum positive moment

The moment is a vector characterizing the action of one body on another body in rotation. The moment was arbitrarily chosen as positive when rotation was upward with respect to the ground. It was maximal when the rotation around the vertical axis was maximum, and zero when the rotation of the body around the vertical axis was null. The moment was calculated by multiplying the modulus of the GRF by the distance from CM. The motion of the arm decreased the maximum positive moment from 86.1 N·m to 76.7 N·m ($F_{1,15}$=8.98; P<0.05). The mean value of the positive peak moment was greater for experts than for novices (+21.5%), ($F_{1,15}$=10.69; P<0.05). The height of the drop jump increased significantly ($F_{1,15}$=41.81; P<0.05) the positive peak moment by 35%. No interaction was found between arm motion, drop height, and expertise (all Fs<1), (Figure 6).

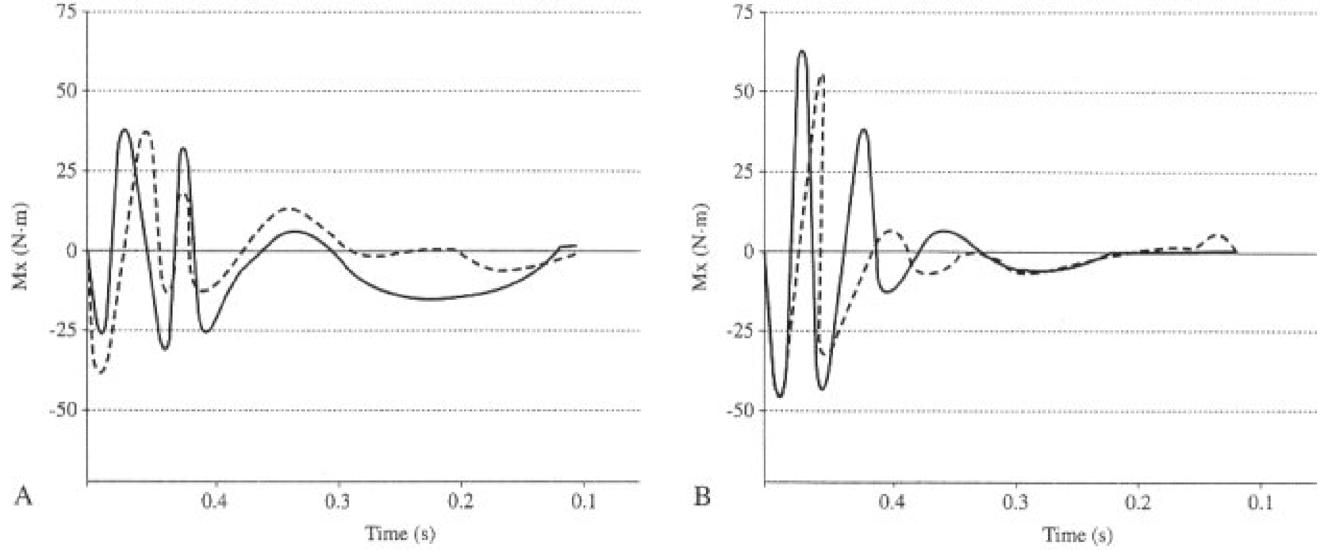

Figure 6.—Typical individual force moment (continuous and dashed lines corresponds to two typical subjects) on the transversal axis (x) of the impulse with arms free (A) and fixed (B).

Maximum negative moment

There was no main effect of arm motion on the maximum negative moment. Experts had a mean value of the negative peak moment of 20.7% greater than novices ($F_{1,15}$=10.15; P<0.05). The dropping condition increased significantly ($F_{1,15}$=10.44; P<0.05) the value of the negative peak moment, from -81.6 N·m (DJ60) to -63.4 N·m (DJ30). No interaction was found between arm motion, drop height, and expertise (all Fs<1).

Leg stiffness

Experts showed higher values of leg stiffness than novices ($F_{1,15}$=7.93; P<0.05), with a mean value of 15.4 kN/m against 9.29 kN/m for novices (+40%). There was no main effect of arm motion on leg stiffness (F<1). The height of the drop jump did not change the value of leg stiffness (F<1). No interaction was found between arm motion, drop height, and expertise (all Fs<1).

Discussion

The first hypothesis that vertical jump performance can be increased by swinging the arms has been validated in this study. Participants were found to jump 7.5 cm (14.5%) higher with arm movements than without. This value is slightly greater than the one found in the standing vertical jump [3] (12.7%). The main factors contributing to this gain in performance appear to be the increase in the vertical position of the center of mass at take-off TO (+4.8 cm), the increase in take-off vertical velocity (+7%), the increase in the active peak of VGRF (+5.5%), and of the relative peak of power (+33%). The present investigation reveals a significant increase by 4.6 cm in DJ30 and by 5 cm in DJ60 in the vertical displacement of the mass center before take-off when arm motion is allowed. The position of the center of mass is primarily influenced by the relative position of all segments. The final body orientation at take-off with the arms upward increases the height of the center of mass because an important part of body mass is located at the top of the body. During jumping without using the arms, the body mass distribution is more homogeneous along the vertical axis. In the context of high jumping, Dapena et al.[1] has shown that the relative position of body segments allows some Fosbury athletes to clear the bar with their center of mass below the bar. Our results are consistent with the literature, in which comparable studies on vertical jump have reported a pre-TO increase of 4.5 cm [12] or 6.1 cm [11] in the vertical displacement of the center of mass. The increase in the vertical velocity at TO is lower for the drop jump than in the standing vertical jump,[11, 12] by about 10%.

Our second hypothesis was that the maximum amplitudes of the positive and negative moments are related to the balance during flight, i.e. we supposed that the maximum amplitudes are in relation with the angular moment at take-off. An analysis of the VGRF profiles (Figure 4) reveals that the magnitude of VGRF appeared earlier in DJRA than in DJFA. The peak value appeared 0.032 s earlier in DJRA. These results are in contradiction with those obtained by Bobbert et al.,[24] indicating that experts optimized their drop jump performance through a bouncing jump rather than a counter-movement jump (shorter impulse time for a better mechanical output). A study of the standing long jump reported by Ashby et al.[25] indicated that subjects might not have used all the available muscles force near the end of the TO phase in the restricted arm motion condition. This could be explained by the complex problem of balancing the body during the impulse. Indeed, the eccentric time differs between conditions, showing an increase of time to peak in the free arm condition. At the same time, the maximum moment showed a significant decrease when the arms are used. This suggests that the high level of constraints of the drop jump increases the eccentric time in order to stabilize the body during the landing phase and only then to push-off for take-off. This behavior is particularly specific to the experts, as we show below.

In addition, the force moment analysis (Figure 6) suggests that the force profile can be explained by the balance constraints during the impulse. Indeed, the law of conservation of angular moment constrains the subject to take off in an optimal orientation because the body's total angular moment cannot be changed during the aerial phase. The force moment is significantly greater in DJRA (+14.6% in DJ60), showing that the role of arm motion is more to be understood in the maintenance of the balance of the system, than in shortening the eccentric phase. Such behavior confirms the role of upper-limb balance reported in standing long jump.[25]

The last hypothesis that was proposed concerns the difference between experts and novices in the vertical jump performance and the mechanical output. First, experts performed higher jumps in DJ60 than in DJ30 (4 cm, +8.5%), while novices performed higher jumps in DJ30 than in DJ60 (2 cm, +6%). Moreover, experts showed significant greater values of leg stiffness (+40%) and power output (+30%) than novices. The greater value of leg stiffness measured on experts could probably be explained by two main factors. First, experts jump with a greater motor ability than novices, as shown by the kinematic patterns. They are more able to practice drop jumping in their training. Second, their muscular properties (greater elastic energy and more ratio of white fibers) allow them to use the stretch shortening cycle during this type of jump, which increases power output [19] and leg stiffness.[2] The values of leg stiffness obtained for the experts in our dropping task (15.4 kN/m) matches the values obtained in various athletic tasks (12-15 kN/m in running;[26] 14-16 kN/m in long jumping,[27] 11.5 kN/m in one-leg vertical jumping.[2] Our kinematic analysis reveals important differences in the use of arm swinging between experts and novices. At touch-down, experts were found to lock their arms in the back, in an extended position (such as in Figure 5), moving backward the center of mass and thus creating a negative force moment (Figure 6). Then, they started to move the arms forward, changing the force moment to positive values. The end of the eccentric phase was characterized by the transition of the arm from the back to the front (Figure 5B), changing quickly the force moment from high negative values to high positive values (Figure 6). Novices, on the contrary, did not show such a shift in the position of the arms from the back to the front. They started to move the arms forward later than experts, increasing the duration of the negative force moment.

In the push-off phase (phase b-c of Figure 5), experts raised and fixed at take-off their arms into a locked arm/forearm position (about 90°-120°), while novices performed a more or less continuous movement (Figure 4C). This descriptive analysis confirms the observations by Dapena *et al.*[1] in the Fosbury-flop, revealing a similar behavior. The push-off phase reveals a better use of arm motion by experts using the throw-and-fix technique, which increases the vertical velocity up to TO (+7.6% for experts vs +6% for novices). Movements of the lower limbs do not appear to have influenced the general kinematics of the jump, with knee and ankle maximum flexion being much closed between novices and experts (no significant difference). Therefore, arm motion in the drop jump appears to be primarily used to control the balance of the postural system, and to reduce the impact at touch-down, rather than to reduce the eccentric phase.

These results have several consequences for training instructions, learning procedure, and prevention, which are now detailed.

First, the role of upper-limb motion allows a better vertical jump performance when the throw-and-fix technique is used. This technique, performed by the experts, requires a specific training, in order to swing the arms with large amplitude, and in synchronization with the actions of the lower limbs. Simple exercises such as holding a medicine ball (*i.e.*, a heavy ball) during jumping upward could be associated with instructions about the throw-and-fix upper-limb motion to learn this technique. This learning phase should necessary be associated with specific exercises and clear instructions about the role of arm swinging.

Second, our study shows that appropriate upper-limb movements by experts decrease the impact shock during the drop jump. This observation encourages prevention during the training of novice jumpers. Indeed, jumping training with novices and young athletes should preferably include simple plyometric exercises, without intense shocks, such as repetitive horizontal bounces, vertical jump over obstacles (hurdles for example), or low dropping jump (below 30 cm), rather than high dropping jump. In fact, high plyometry (drop jump over 30 cm) should be practiced only after a complete muscle strengthening program, including squat jumps, low plyometric exercises.

Conclusions

Skilled jumpers (volley-ball players) were found to have a better use of arm motion than novices in (i) increasing the vertical jump performance (+14%), (ii) controlling the balance of the body at take-off (iii) leaving the ground with an optimal body orientation. The motion of the arms during the jumps was found to increase the jump height by 15% for the volleyball players and 12% for unskilled jumpers, confirming the importance of the role of upper-limb motion during the jumps. Volleyball players performed better in the 60 cm than in 30 cm drop height (+8.5%), showing a better used of elastic energy. Two different behaviors have been identified: experts jump with a longer eccentric time when using arm motion, in order to stabilize the system, and then used a throw and fixed arm motion at take-off. Novices don't changed the eccentric time of the jumps in the two conditions, and used a continuous movement of the arm during the take-off, who seems to be an inefficient strategy.

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