HOW DOES ARM MOTION ENHANCE VERTICAL JUMP PERFORMANCE- A SIMULATION STUDY

Hui-Chieh Chen, Hui-Chuan Chen, and Kuangyou B. Cheng*

Institute of Physical Education, Health, and Leisure Studies, National Cheng Kung University, Tainan, Taiwan

The mechanisms enabling the arms to increase standing vertical jump height are investigated by computer simulation. The human models actuated by joint torque generators consist of four/five segments connected by frictionless joints. Simulation initiates from a balanced static posture and ends at jump takeoff. Joint activation timings are optimized to produce maximum Jump height. Jumping performance is enhanced by arm motion in increased mass centre height and takeoff vertical velocity, which contributes about 1/3 and 2/3 to the increased height, respectively. Arm swing also elongates the durations of hip torque generation and ground contact period. Theories explaining the performance enhancement caused by arms are examined. Because shoulder joint force due to arm motion does not precisely reflect in the changes of vertical ground reaction force, the force transmission theory is doubtful. The joint torque/work augmentation theory is accepted at the hip but not knee and ankle because only the hip joint work is considerably increased. Since shoulder joint work is responsible for around half of the additional energy created by arm motion, the pull/impart energy theory is also granted.

KEY WORDS: jumping, joint torque, activation, optimization, coordination

INTRODUCTION:

Arm swing has been shown to increase jump height by about 10% or more (Feltner et al., 1999; Harman et al., 1990; Shetty and Etnyre, 1989). Both increased center of mass (CM) height at takeoff and greater vertical velocity are responsible for increased jump height.

Numerous studies investigated the reasons for raised takeoff vertical velocity when the arms are used. First of all, increased ground reaction force (GRF) in the latter half of the propulsive phase, leading to enhanced net ground reaction impulse and larger takeoff velocity, has been shown to be the results from arm swing (Harman et al., 1990; Payne et al., 1968; Shetty and Etnyre, 1989). However, simulation (Dapena, 1999) and experiments (Harman et al., 1990) suggested that using only the theory of force transmission (Dapena, 1993) would be too simplistic. Secondly, downward reaction force acting on the trunk and lower body can be induced by upward acceleration of the arms. This would result in reduced upward velocity in the propulsive phase (Harman et al., 1990), but eventually generate greater takeoff velocity. Conversely, Lees et al. (2004) rejected this joint torque augmentation theory because less joint power is generated in arm swing jumps. The third explanation for increased takeoff velocity is the “pull” theory (Harman et al., 1990; Lees et al., 2004). That is, the net force at the shoulder joint acts to pull the trunk up near takeoff when the arms start to decelerate. Energy transfer from the arms to the rest of the body can be caused by this mechanism.

Although it has been demonstrated that arm swing can indeed help increase jump height, contradictory results have been reported. Arm swing was found to decrease, increase, or have insignificant effects on knee and ankle joint torque/work production. Feltner et al. (2004) suggested that this inconsistency may be due to different proficiency level of the subjects recruited.

The purpose of this study is to investigate the mechanisms enhancing vertical jumping performance by arm motion. Forward simulation is chosen for the present study because it yields precise results and avoids disadvantages (e.g. incorrect data recording or subject skill/psychological factors) in actual experiments.

METHOD:

The standing vertical jumping from a static squat posture to takeoff is simulated by a four-segment (4S) and five-segment (5S) planar human body models. Segments represent feet, shanks, thighs, and head-arms-trunk (HAT) in model 4S. In model 5S the HAT is partitioned into head-trunk (HT) and arms with fixed elbow joint (Ashby and Delp, 2006). Movement is driven by torque actuators at the ankle, knee, hip, and shoulder. Equations of motion are generated by the software AUTOLEV (www.autolev.com). Each joint torque T generated is assumed to be the product of three factors:

$$T = T_{\max}(\theta)h(\omega)A(t) \qquad (1)$$

$T_{\max}(\theta)$ depending on joint angle is the maximum isometric torque (effective torque for both extremities). The dependence on joint angular velocity is modeled by $h(\omega)$.

$$\begin{cases} h(\omega) = (\omega_0 - \omega)/(\omega_0 + \Gamma\omega), & \omega/\omega_0 < 1 \\ h(\omega) = 0, & \omega/\omega_0 \ge 1 \end{cases} \qquad (2)$$

where ω is the instantaneous joint angular velocity (positive in extension), ω_0=±20 rad/s is maximum extension angular velocity, and constant Γ=2.5 is a shape factor. Joint activation level $A(t)$ characterizing the coordination strategy corresponds to the effective activation of muscles across the joint. The activation level $0 \le A(t) \le 1$ is modelled by an exponential function similar to that of Selbie and Caldwell (1996) with some modifications.

$$\begin{cases} A = A_i, & t \le t_0 \\ A = A_i \exp(-(t-t_0)/\tau_{deact}), & t_0 < t \le t_0 + t_1 \\ A = 1 - \exp((t_0 + t_1 - t)/\tau_{act}) + A_i \exp(-(t-t_0)/\tau_{deact}), & t > t_0 + t_1 \end{cases} \qquad (3)$$

A_i represents the initial activation. τ_{act} and τ_{deact} are muscle activation rise and decay time constants. t_0 is the period for remaining the initial activation. t_1 is the time elapsed from t_0 to the instant when extension activation begins. The current model assumes a static initial posture, and joint initial $A(t)$ for holding this posture is calculated. The objective is to maximize is jump height J_0:

$$J_0 = (y_f + v_f^2/2g) \qquad (4)$$

where y_f and v_f are CM vertical position and velocity at the takeoff instant t_f.The optimization algorithm adopted is the downhill simplex method. Varying initial guesses and re-starting the optimization from a newly found optimum are employed to increase the likelihood of finding the global rather than a local optimum.

RESULTS:

Maximum height is 0.091 m more with arm motion. Around 37.8% of the height increase is due to higher CM at takeoff, leaving the remaining 62.2% to the increased velocity. Contact duration and total work done are also larger with arm motion (Table 1).

Table 1 Features of simulated jumps with (5S) and without (4S) arm motion

	4S	5S
CM height at takeoff (m)	0.9296	0.9639
CM vertical velocity at takeoff (m/s)	2.5095	2.7213
Maximum CM height after takeoff (m)	1.2506	1.3413
Total contact duration (s)	0.4344	0.5831
Ankle joint work (N-m)	104.2856	96.8006
Knee joint work (N-m)	104.8377	86.2193
Hip joint work (N-m)	163.3235	239.6418
Shoulder joint work (N-m)	N/A	54.7499
Work done during contact (N-m)	372.4469	477.4116

The GRF pattern in the optimal 5S jump has a shorter upward thrust duration compared to the 4S jump but a larger force value prior to takeoff. In searching for the optimum, another pattern (5Sa) which yields slightly lower jump height contains longer upward thrust duration but the maximum GRF is close to that of the 4S jump. Shoulder force applied to the arms is mostly positive throughout ground contact duration. This means that the arms pull the trunk up for only a short period of time (Fig. 1). Joint work is 7% less in the ankle, 18% less in the knee, but 47% more in the hip compared to no-arm jump (Table 1). Together with the addition shoulder joint work, total work produced is 28% more in the 5S jump.

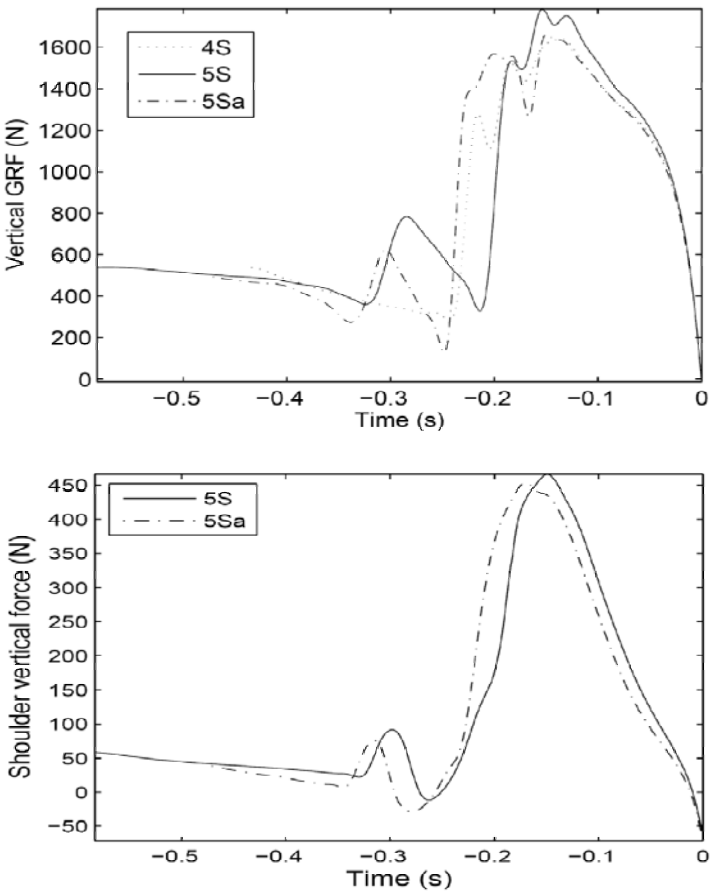

Figure 1: Vertical GRF patterns (top) and shoulder force (bottom).

DISCUSSION:

Comparison of simulated kinematics with previous experimental results shows that current models produce reasonable motions. Activation begins in the order of knee, hip, and ankle for the 4S jump and hip, shoulder, knee, and ankle for the 5S jump. This generally concurs with previous 4S jumping simulations (Selbie and Caldwell, 1996) but seems to disagree with the proximal-to-distal strategy (Bobbert and Ingen Schenau, 1988). In searching for the optimal 4S jump, almost simultaneous knee and hip onset or slightly earlier knee activation was also found to yield suboptimal jump heights near the present optimum. Although in the 5S jumping actual shoulder activation starts after hip activation, forward shoulder motion begins earlier than hip extension, which is consistent with the proximal-to-distal strategy.

The force transmission theory is doubtful because shoulder joint force does not necessarily correspond to larger GRF despite some correlation in their patterns is observed (Fig. 1). Simulation results reveal that previous observation of increasing vertical GRF later in the propulsion phase (Harman et al., 1990) or lengthening contact duration (Feltner et al., 2004) are both possible techniques used and deemed optimal by different subjects.

The torque/work augmentation theory is confirmed only in the hip joint. Knee joint work is decreased in the 5S jump mainly because of decreased duration of torque generation. Ankle joint work is slightly reduced with arm motion, but in some suboptimal results (e.g. 5Sa) it is slightly increased.

Since the arms pull the trunk up for even shorter time (Fig. 1) than previously reported (Lees et al., 2006) and shoulder joint work is responsible for 52% of the increased total work, the “pull” theory is better rephrased as the “impart energy” theory (Ashby and Delp, 2006).

CONCLUSION:
Simulations have confirmed that arm motion can enhance jumping performance and the increased takeoff vertical velocity contributes nearly 2/3 to the increased height. Arms also cause earlier onset of hip torque and lengthen ground contact duration. Since the force on shoulder due to arm motion is not closely related to changes in vertical GRF, the force transmission theory is questionable. The torque/work augmentation theory applies only to the hip. Shoulder joint work is responsible for about half of the additional energy resulting from arm swing, which supports the pull/impart energy theory.

REFERENCES:
Ashby, B.M. & Delp, S.L. (2006). Optimal control simulations reveal mechanisms by which arm movement improves standing long jump performance. *Journal of Biomechanics* 39, 1726-1734.
Bobbert, M.F., Ingen Schenau & G.J. van (1988). Coordination in vertical jumping. *Journal of Biomechanics* 21, 249-262.
Dapena, J. (1999). A biomechanical explanation of the effect of arm actions on the vertical velocity of a standing jump. *Proceedings of the XVIIth Congress of the International Society of Biomechanics.* Calgary, Canada.
Feltner, M.E., Bishop, E.J. & Perez, C.M. (2004). Segmental and kinetic contributions in vertical jumps performed with and without an arm swing. *Research Quarterly for Exercise and Sport* 75, 216-230.
Feltner, M.E., Fraschetti, D.J. & Crisp, R.J. (1999). Upper extremity augmentation of lower extremity kinetics during countermovement vertical jumps. *Journal of Sports Sciences* 17, 449-466.
Harman, E.A., Rosenstein, M.T., Frykman, P.N. & Rosenstein, R.M. (1990). The effect of arms and countermovement on vertical jumping. *Medicine and Science in Sports and Exercise* 22, 825-833.
Lees, A., Vanrenterghem, J. & Clercq, D.D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics* 37, 1929–1940.
Selbie, W.S. & Caldwell, G.E. (1996). A simulation study of vertical jumping from different starting postures. *Journal of Biomechanics* 29, 1137-1146.
Shetty, A.B. & Etnyre, B.R. (1989). Contribution of arm movement to the force components of a maximum vertical jump. *Journal of Orthopaedic and Sports Therapy* 11, 198–201.

Acknowledgement
This research was partially supported by the National Science Council in Taiwan (NSC 94-2213-E-006-037) and National Cheng Kung University Research Grant (950115) for optimization calculations.