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The mechanisms that enable arm motion to enhance vertical jump performance—A simulation study

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Abstract

The reasons why using the arms can increase standing vertical jump height are investigated by computer simulations. The human models consist of four/five segments connected by frictionless joints. The head–trunk–arms act as a fourth segment in the first model while the arms become a fifth segment in the second model. Planar model movement is actuated by joint torque generators. Each joint torque is the product of three variable functions of activation level, angular velocity dependence, and maximum isometric torque varying with joint angle. Simulations start from a balanced initial posture and end at jump takeoff. Jump height is maximized by finding the optimal combination of joint activation timings. Arm motion enhances jumping performance by increasing mass center height and vertical takeoff velocity. The former and latter contribute about 1/3 and 2/3 to the increased height, respectively. Durations in hip torque generation and ground contact period are lengthened by swinging the arms. Theories explaining the performance enhancement caused by arms are examined. The force transmission theory is questionable because shoulder joint force due to arm motion does not precisely reflect the change in vertical ground reaction force. The joint torque/work augmentation theory is acceptable only at the hips but not at the knees and ankles because only hip joint work is considerably increased. The pull/impart energy theory is also acceptable because shoulder joint work is responsible for about half of the additional energy created by arm swings.

Keywords: Jumping; Joint torque; Activation; Optimization; Coordination

1. Introduction

Execution of a standing vertical jump is usually accompanied by swinging the arms, and accordingly the effects of arm swings on performance have been studied for decades. Jump height has been shown to increase by about 10% or more due to the use of arms (Feltner et al., 1999; Harman et al., 1990; Payne et al., 1968; Shetty and Etnyre, 1989). The increased height consists of increased center of mass (CM) height at takeoff and higher flight height attributed to increased vertical velocity. The former portion results mainly from the elevated arms and contributes about 54% (Feltner et al., 2004), 43% (Feltner et al., 1999), or 28% (Lees et al., 2004). This leaves the raised velocity contributing between 46% and 72%.

The reasons why using the arms can generate larger vertical velocity at takeoff have been investigated intensively. Firstly, arm swing was shown to help increase ground reaction force (GRF) in the latter half of the propulsive phase, leading to enhanced net ground reaction impulse and raised takeoff velocity (Harman et al., 1990; Payne et al., 1968; Shetty and Etnyre, 1989). However, experiments (Harman et al., 1990) and simulations (Dapena, 1999) suggested that merely using the theory of force transmission (Dapena, 1993; Payne et al., 1968) to explain increased takeoff velocity is too simplistic an idea. Feltner et al. (2004) later reported that greater vertical impulse in arm-swing jumps is not due to greater vertical GRF but to a trend in the increased duration of the propulsive phase. This finding also suggests the involvement of more complicated mechanisms other than simply force transmission caused by arm motion.

Secondly, researchers proposed that slower extension of the lower extremities and consequently greater muscle force

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production (due to the force–velocity relation) can result from arm swinging. This is because upward acceleration of the arms can cause a downward reaction force to act on the rest of the body, resulting in reduced upward velocity in the propulsive phase (Dapena and Chung, 1988; Harman et al., 1990), but eventually greater takeoff velocity can be generated by this mechanism. This theory was further supported by the studies of Feltner et al. (1999) and Hara et al. (2006). Feltner et al. (2004) also reported that although the arm swing decreases the ability of the lower extremities to generate extension torque early in the propulsive phase, it augments the torque production ability later in this phase. On the other hand, Lees et al. (2004) rejected this joint torque augmentation theory because less joint power is generated in arm swing jumps. However, the key attribute contributing to jump height is the total system energy at takeoff, which comes from work done rather than power production during ground contact (Ashby and Delp, 2006).

The third explanation for increased takeoff velocity is the "pull" theory (Harman et al., 1990; Lees et al., 2004). That is, when the arms start to decelerate near takeoff, the net force at the shoulder joint acts to pull the trunk up. This causes energy to be transferred from the arms to the rest of the body. This theory was supported by a vertical jump study (Lees et al., 2004) and standing long jump simulations and was referred to as the "impart energy" theory (Ashby and Delp, 2006).

Despite the well-established fact that arm swing can help increase jump height, contradictory results have been reported. Knee joint torque/work was found to decrease in arm swing jumps (Ashby and Delp, 2006; Feltner et al., 2004; Hara et al., 2006) but no difference (Lees et al., 2004) or a 28% increase was also reported (Feltner et al., 1999). Ankle joint torque/work was shown to increase in most studies but virtually no difference (Feltner et al., 1999; Lees et al., 2004) has also been reported. Feltner et al. (2004) suggested that this inconsistency may be due to different proficiency levels of the subjects in these studies. In addition, since most people are used to jumping with arms, the no-arm jumps performed may not be optimal. Such kinds of proficiency-related factors are difficult to control in experimental studies. Moreover, errors in data recording (Lees et al., 2004) and those due to data smoothing are inevitable.

The purpose of this study is to investigate the mechanisms enhancing vertical jumping performance by swinging arms. Since forward simulations employing numerical integration can be performed to any desired accuracy and can avoid disadvantages (e.g. incorrect data recording or subject skill/psychological factors) in actual experiments, it serves as the best tool for the present study.

2. Methods

Four-segment (4S) and five-segment (5S) planar human body models are used to simulate the standing vertical jumping from initiation to takeoff. Frictionless hinge joints connect body segments (Fig. 1). In the 4S model segments represent feet, shanks, thighs, and head–arms–trunk (HAT). In the 5S model the HAT is partitioned into head–trunk (HT) and arms with fixed elbow joint (Ashby and Delp, 2006). The origin of each model is at the balls of feet. Model parameters are listed in Appendix A.

Since the focus of this study is the effect of arm motion, simulations start from a static squat rather than a straight posture to reduce the effect of countermovement. Torque actuators at the ankle, knee, hip, and shoulder are used to drive model movement. Rather than modeling individual muscle function, these torque actuators represent the total contributions of joint extensors (Selbie and Caldwell, 1996). Equations of motion are generated by AUTOLEV (http://www.autolev.com), a dynamics symbol manipulator.

Each joint torque T generated is assumed to be the product of three factors:

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

$T_{\max}(\theta)$ is the maximum isometric torque (effective torque for both extremities), which depends on joint angle. Function $h(\omega)$ models the dependence on joint angular velocity. Thus the features of muscle force production depending on maximum isometric force, muscle length, and shortening velocity are preserved. Joint activation level $A(t)$ corresponds to the effective activation of muscles across the joint and characterizes the coordination strategy.

Functions $T_{\max}(\theta)$ for the ankle, knee, and hip are based on Pandy et al. (1990) and Hoy et al. (1990). Shoulder $T_{\max}(\theta)$ is taken from Otis et al. (1990). Angular velocity dependence $h(\omega)$ is given by (Selbie and Caldwell, 1996):

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

Here ω is the instantaneous joint angular velocity (positive in extension), $\omega_0 = \pm 20$ rad/s is the maximum extension angular velocity, and $\Gamma = 2.5$ is a shape factor. The effect of eccentric muscle contraction is considered by increasing $h(\omega)$ to a saturation value of 1.5 when $\omega(t) < 0$ (Fig. 2).

The activation level $0 \leqslant A(t) \leqslant 1$ is modeled by an exponential function similar to that of Selbie and Caldwell (1996) but some modifications are made. This is because previous simulations do not start from balanced positions, which are physically impractical to real jumping. The current model assumes a static initial posture with calculated initial joint $A(t)$ for holding this posture. The general activation pattern consists of maintaining the initial value followed by slightly reducing (relaxing) and then increasing to full activation (maximum-effort extension), which mimics actual jumping strategies. To avoid the possibility of moving up and down without takeoff, it is assumed that once $A(t)$ starts to increase, it cannot be

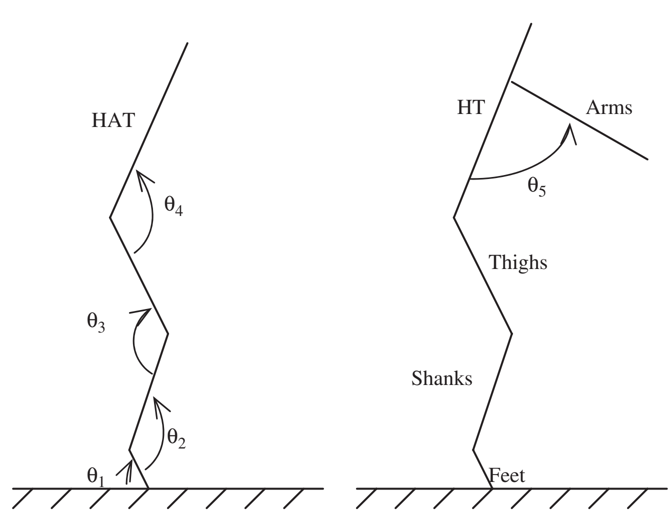

Fig. 1. Planar four- and five-segment models actuated by joint torque generators are used to simulate vertical jumping.