DIFFERENCES BETWEEN JUMPING AND SOMERSAULTING FROM A DIVING SPRINGBOARD: A SIMULATION STUDY

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Maximum-height jumping and jumping for maximizing backward somersault rotations are simulated. The springboard is modeled by a rigid bar with point mass on the tip and a rotational spring on the other hinged end. The planar 4-segment human model is driven by torque actuators at the ankle, knee, and hip. Movement simulation begins from a balanced initial posture and stops at jump takeoff. The objective is to find joint torque activation patterns during board contact so that jump height or the number of backward rotations in flight (determined by takeoff kinematics) is maximized. Kinematic differences between jumps maximizing backward rotations and jumps maximizing height lie mainly in reduced knee angular velocity and consequently bent knees at takeoff. In addition, more significant hip flexion torque/activation is found in jumps maximizing rotations than that in maximum-height jumps. With reasonable model assumption, this kind of information may be useful for athletic training.

KEY WORDS: optimization, diving, surface compliance, muscular activation

INTRODUCTION: Jumping from compliant surfaces for maximal somersault rotations is one of the key features in various sports (e.g. trampoline jumps, gymnastics, and springboard diving). Maximal-height jumping from a diving springboard has been studied (Cheng & Hubbard, 2004 & 2005), but how the segment coordination strategies are adjusted for maximal somersault rotations is not clear. Although somersaulting from a compliant surface was simulated in tumbling gymnasts (King & Yeadon, 2004), the ground contact duration is short (~0.1s). Thus it is different to depict how the control strategies as functions of time are different from those in pure jumping.

Studies in springboard diving have focused on running dive kinematics (Jones & Miller, 1996) or springboard tip kinematics (Jones & Miller, 1996; Miller et al., 1998), but no comparison in control strategy between pure- and somersaulting jumps was found. It is generally accepted that using computer simulation to study human movement may avoid undesired psychological or environmental factors influencing performance, and simulation with reasonable models will even provide guidelines for coaching athletes. Therefore, the purpose of this study is to use model simulation to investigate how the kinematic and coordination (joint torque activation patterns) characteristics in jumps for backward somersaults differ from those in maximum-height jumping on a diving springboard.

METHODS: The human model has four segments: feet, shanks, thighs, and HAT (head-arms-trunk) with the toe point (actually the ball) attached to the board tip (Figure 1). Segments are connected by frictionless revolute joints and are actuated by joint torque actuators at ankle, knee, and hip joints to perform a backward standing jump. These joint torques represent total contributions of muscles acting across the ankle, knee, and hip.

The springboard is modeled by a rigid bar with a point mass on one end and a rotational spring on the other end (Kooi & Kuipers, 1994). Equivalent board mass, bar length, and rotational spring constant at different fulcrum settings are obtained according to a previous study (Miller et al., 1998).

Each active joint torque T is the product of maximum torque T_{max} and 3 functions: angle dependence $f(\theta)$, angular velocity dependence $h(\omega)$, and activation level $A(t)$:

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

Angle dependence $f(\theta)$ is from Pandy et al. (1990) and Hoy et al. (1990) for extension and flexion, respectively. Angular velocity dependence $h(\omega)$ is modeled from a previous study (Selbie and Caldwell, 1996):

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

where ω_0 is maximum joint extension (positive) or flexion (negative) angular velocity, ω is instantaneous joint angular velocity (positive meaning joint extension), and Γ is a constant shape factor. Values for ω_0 and Γ are ±20 rad/s and 2.5, respectively (Selbie and Caldwell, 1996). If $\omega(t)$ and $A(t)$ have different signs (eccentric muscle contraction), $h(\omega)$ can be increased to a saturation value of 1.5.

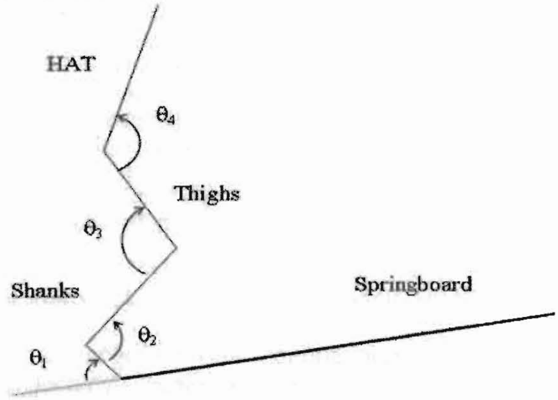

Figure 1 Body segments and springboard are connected by frictionless revolute joints.

Joint activation level *A(t)* is approximated by a cubic spline fit of 9 nodal values at equally spaced time instants throughout board contact. Fixed initial nodes of *A(t)* correspond to static equilibrium at the beginning of jumping movement. Since muscular activation cannot change instantaneously, *dA/dt* is constrained. An activation time constant of 80 ms, near the geometric mean of muscle activation rise and decay time constants, typically taken to be 20 and 200 ms (Pandy et al., 1990), is assumed in this study. Thus, $|dA/dt| \leq 1/0.08\ s^{-1}$.

The control goal is find the set of joint activation nodal values and takeoff time t_f to maximize the objective function $J_1 = y_f + v_f^2/2g$ for maximum-height jumping or $J_2 = \theta + t_{air} \times H_{tot}/I_{tot}$ for maximal backward somersault rotations. Here y_f and v_f are center of mass (c.m.) vertical position and velocity at t_f, g is the gravitational acceleration, θ is the angle measured from the vertical axis to the line joining board tip and body c.m. at takeoff; H_{tot} and I_{tot} are the takeoff total angular momentum and moment of inertia about body c.m., respectively; t_{air} is flight time determined by diver c.m. vertical velocity at takeoff. This means that both the objective functions depend on the linear and/or angular positions and velocities and the end of board contact. To find the global rather than a local maximum, the downhill simplex method (Press, 1997) with varying initial guesses and re-starting the optimization from newly found optimum was employed.

RESULTS: Maximum-height jumping (4SJ) and maximum-rotation jumping (4SR) simulations at fulcrum = 5 are compared (Figure 2). Since experimental validation of the model has been shown elsewhere (Cheng & Hubbard, 2005), only simulation results are included here. *Although the board contact duration (around 0.85 s) is slightly different in each case,* for comparison it is normalized to be from 0 to 1. Movements of 4SJ and 4SR are very similar except for partially extended knee at takeoff in 4SR. While all joints undergo the flexion-extension pattern, maximum hip flexion (minimum hip angle) occurs latest. Joints achieve maximum angular velocity (not shown here) near or at takeoff.

Although joint torque/activation patterns are similar in both cases (Figure 3), some noticeable differences exist in the hip and the knee. Hip flexion activation is smaller (less negative) in 4SJ. Maximum hip and knee torques are larger in 4SR. The knee remains fully activated for shorter time in 4SJ (Figure 3b). Relaxation and minor flexion (negative) activation followed by full extension activation is observed in all joints.

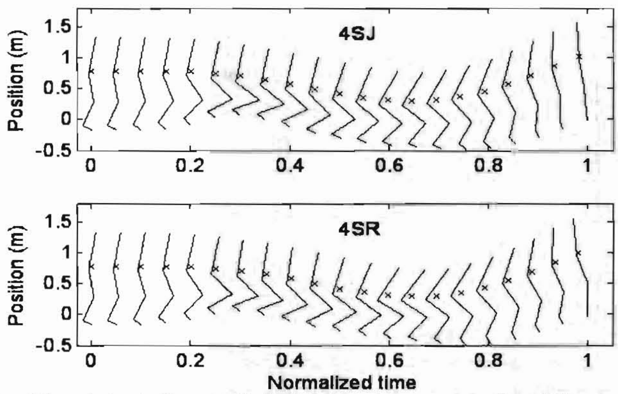

Figure 2 Simulated diver stick figures vs. normalized time. Symbol 'x' denotes c.m. position.

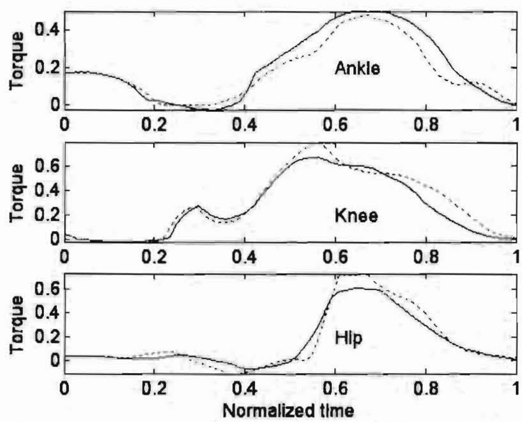

Figure 3a Simulated torques for 4SJ (—) and 4SR (...) at each joint. Torque is normalized by dividing by its maximum isometric value.

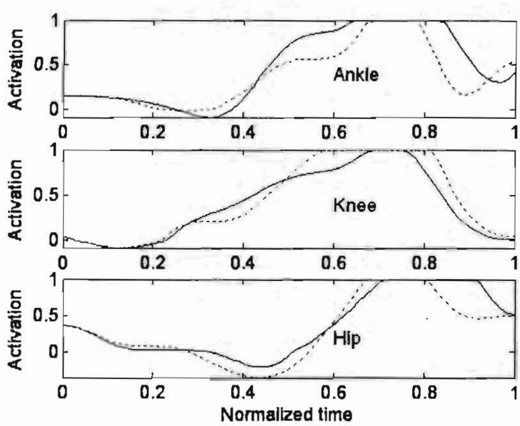

Figure 3b Simulated joint activation for 4SJ (—) and 4SR (...) at each joint. The relaxation-flexion-extension activation pattern is found in all joints.

DISCUSSION: When the performance criterion changes from maximizing jump height (4SJ) to maximizing backward rotations (4SR), the most distinguishable kinematic difference is observed at the knee (Figure 2). With fixed hip angle, extending the knees will cause body forward rotation, which is not favorable in backward somersault rotation. This might be why the knee angular velocity is decreased considerably near the end of contact, which results in bent knees at takeoff. The results also show decreased hip angular velocity near takeoff. This is probably because excessively large hip angular velocity and a backward bent posture may result in smaller takeoff vertical velocity, which reduces the time in the air.

In maximum-rotation jumps from compliant surfaces, joint full activation occurs around maximal board deflection when the board is best able to resist, which resembles that of maximum-height jumps (Figure 2 & 3b). This is because the most muscular work is done in this way, leading to higher upward velocity and larger total angular momentum. One noticeable difference between jumps maximizing height and jumps maximizing backward rotations lies in earlier and larger hip flexion activation/torque in the latter (Figure 3). This countermovement seems to result in larger hip torque which help angular momentum generation. The reason that maximum knee torque is larger in 4SR is likely because the knee is not fully extended at takeoff. This posture facilitates torque generation (according to the angle-torque dependence) compared to straight knee condition.

CONCLUSION: In comparing jumps maximizing backward somersault rotations with those maximizing height from a springboard without arm motion, the most distinguishable differences lie in the knee kinematics. Joint activation and torque patterns in somersaulting jumps are similar to those in pure jumping in terms of the general relaxation, minor flexion, maximal extension, and reduced extension pattern. One noticeable difference appears in larger hip flexion in somersaulting jumps.

REFERENCES:

Cheng, K.B. & Hubbard, M. (2004). Optimal jumping strategies from compliant surfaces: a simple model of springboard standing jumps. *Human Movement Science*, 23, 35-48.

Cheng, K.B. & Hubbard, M. (2005). Optimal compliant-surface jumping: a multi-segment model of springboard standing jumps. *Journal of Biomechanics* (in press).

Hoy, M.G., Zajac, F.E., & Gordon, M.E. (1990). A musculoskeletal model of the human lower extremity: the effect of muscle, tendon, and moment arm on the moment-angle relationship of musculotendon actuators at the hip, knee, and ankle. *Journal of Biomechanics*, 23, 157-169.

King, M.A. & Yeadon, M.R. (2004). Maximising somersault rotation in tumbling. *Journal of Biomechanics*, 37, 471-477.

Kooi, B.W. & Kuipers, M. (1994). The dynamics of springboard. *International Journal of Sport Biomechanics*, 10, 335-351.

Jones, I.C. & Miller D.I. (1996). Influence of fulcrum position on springboard response and takeoff performance in the running approach. *Journal of Applied Biomechanics*, 12, 383-408.

Miller, D.I., Osborne, M.J. & Jones, I.C. (1998). Springboard oscillation during hurdle flight. *Journal of Sports Sciences*, 16, 571-583.

Press, W.H. (1997). *Numerical recipes in C*, 2nd Ed. Cambridge University Press, New York.

Selbie, W.S. & Caldwell, G.E. (1996). A simulation study of vertical jumping from different starting postures. *Journal of Biomechanics*, 29, 1137-1146.