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Evaluation of a subject-specific female gymnast model and simulation of an uneven parallel bar swing

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ABSTRACT

A gymnast model and forward dynamics simulation of a dismount preparation swing on the uneven parallel bars were evaluated by comparing experimental and predicted joint positions throughout the maneuver. The bar model was a linearly elastic spring with a frictional bar/hand interface, and the gymnast model consisted of torso/head, arm and two leg segments. The hips were frictionless balls and sockets, and shoulder movement was planar with passive compliant structures approximated by a parallel spring and damper. Subject-specific body segment moments of inertia, and shoulder compliance were estimated. Muscles crossing the shoulder and hip were represented as torque generators, and experiments quantified maximum instantaneous torques as functions of joint angle and angular velocity. Maximum torques were scaled by joint torque activations as functions of time to produce realistic motions. The downhill simplex method optimized activations and simulation initial conditions to minimize the difference between experimental and predicted bar-center, shoulder, hip, and ankle positions. Comparing experimental and simulated performances allowed evaluation of bar, shoulder compliance, joint torque, and gymnast models. Errors in all except the gymnast model are random, zero mean, and uncorrelated, verifying that all essential system features are represented. Although the swing simulation using the gymnast model matched experimental joint positions with a 2.15 cm root-mean-squared error, errors are correlated. Correlated errors indicate that the gymnast model is not complex enough to exactly reproduce the experimental motion. Possible model improvements including a nonlinear shoulder model with active translational control and a two-segment torso would not have been identified if the objective function did not evaluate the entire system configuration throughout the motion. The model and parameters presented in this study can be effectively used to understand and improve an uneven parallel bar swing, although in the future there may be circumstances where a more complex model is needed.

1. Introduction

The Fédération Internationale Gymnastique (FIG) continuously reviews and changes gymnastics rules to foster new skill development, and increase required difficulty and safety (FIG, 2007). New maneuvers that satisfy requirements are typically conceptualized by coaches and developed by modifying a technique until the maneuver is successfully completed. The maneuver is then taught to other gymnasts with little understanding about how differences in body size or strength might change the optimal technique.

Using computer simulation may be faster and safer when perfecting current maneuvers and creating new ones. Simulations can investigate how each joint angle change contributes to the overall performance, and how optimal performances depend on moments of inertia and strength properties. Other possible gymnast benefits include comparing current and optimal performances and visualizing new maneuvers prior to performing them.

Before creating or perfecting uneven parallel bar maneuvers using computer simulation, models must be evaluated to determine whether they are complete enough to predict realistic motion. The need to examine how well computer models correspond to reality has been discussed for more than 30 years (Miller, 1974; Panjabi, 1979; Yeadon and King, 2002). Protocols for simulation evaluation have been outlined, but none have been universally adopted because the represented systems are complex and simulation applications vary widely.

Researchers simulating human movement using muscle-force-driven forward dynamics models even use different simulation

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evaluation criteria. Some researchers evaluate a simulation's ability to predict key experimental performance features rather than the entire motion (Yeadon and King, 2002; Hiley and Yeadon, 2005), and some evaluate the entire motion by using directly measured values such as joint center (JC) position time histories or derived quantities such as joint angle or whole body CM position time histories (Koh and Jennings, 2003). Other times, researchers use a combination of key performance features and parameter time histories to evaluate the model (Hiley and Yeadon, 2007). Sometimes subject-specific human models and individual experimental data are evaluated (King and Yeadon, 2002; Koh and Jennings, 2003). Other times generalized models and group data are used (van Soest et al., 1993; Pandy and Zajac, 1991). All vary different model parameters to match experimental and simulated performances. Although questions may be answered using simulations evaluated with each criterion, individual gymnastics performances are best investigated with a subject-specific model that can simulate the entire motion.

While criteria for simulation evaluation (validation) are subjective, most agree that evaluation is necessary. If the gymnast simulation were used to examine performance without being evaluated, isolating the effects of model assumptions and simplifications would be difficult. This paper aims to define an uneven parallel bar model, estimate gymnast model moments of inertia, maximum instantaneous joint torques and shoulder-joint compliance, and to evaluate the gymnast model's ability to predict an experimental gymnastics swing.

2. Methods

A forward dynamics simulation of a swing prior to dismount on the uneven parallel bars was evaluated by comparing a simulated and experimental performance. After creating models for the compliant uneven bar and subject-specific female gymnast, separate experiments measured shoulder stiffness and damping, and maximum instantaneous joint torques. A former collegiate gymnast (mass = 60.6 kg, height = 1.58 m, age = 27years) gave informed consent for these tests in accordance with the protocol approved by the UCD Internal Review Board.

The bar with a radius of 0.02 m, was modeled as linearly elastic with friction between the bar and concentric hand. Stiffness was determined by applying known forces to the bar-center and measuring deflection. Friction was measured using a pendulum attached to the bar with a typical gymnast leather hand grip. The pendulum was displaced, and resulting decaying amplitude oscillations were recorded. The frictional torque was the product of the coefficient of friction, bar radius, and normal force. The coefficient of friction was varied in a MATLAB model of the system until experimental and simulated amplitude decays matched.

A seven-degree-of-freedom, four-segment gymnast model had torso/head, arm, and two leg segments (Fig. 1) because in a deduction-free performance the

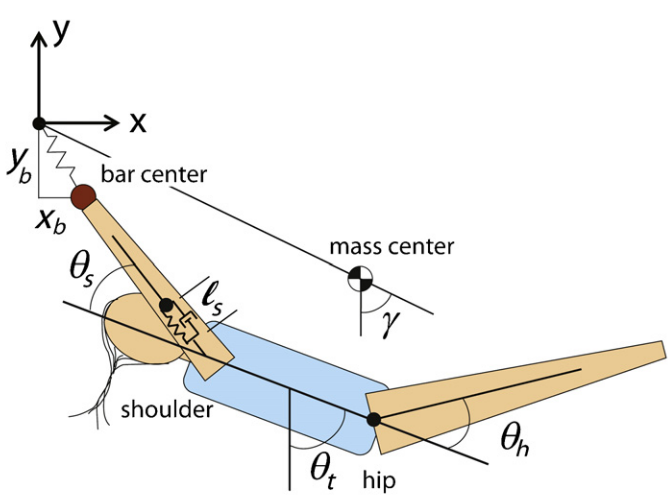

Fig. 1. Seven-degree-of-freedom gymnast model composed of torso/head, arm and two leg segments.

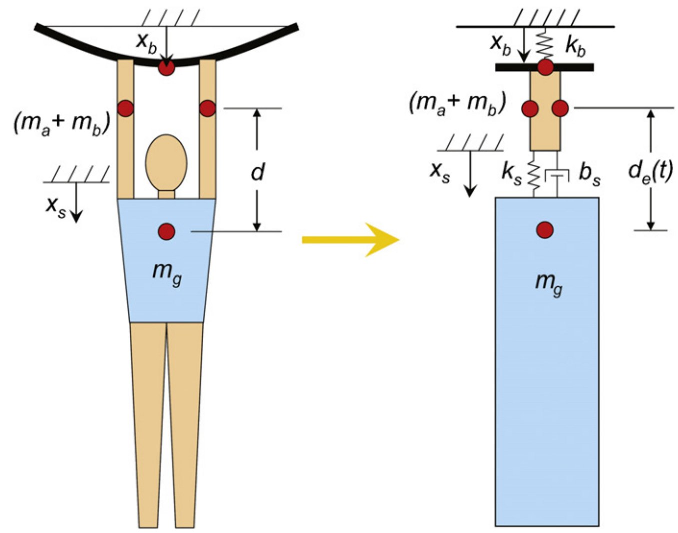

Fig. 2. The gymnast was modeled as a mass–spring–damper system to estimate shoulder stiffness and damping, k_s and b_s, from experimentally measured $d_e(t)$.

hip joint and shoulders can rotate but elbows and knees cannot. Arm motion is restricted to the sagittal plane and hips are frictionless ball-and-sockets. Passive shoulder structures are represented by a parallel spring and damper, with experimentally determined properties. Body segment moments of inertia, masses, and mass centers (CM) were estimated with the inertia model of Yeadon (1990) using 95 measurements. The total estimated mass was corrected to match the actual gymnast mass by scaling all limb masses equally.

Shoulder stiffness, k_s, and damping, b_s, were experimentally determined from bar and gymnast vertical oscillations when released from non-equilibrium initial positions. Two 240 Hz motion analysis cameras recorded vertical oscillations of markers on the sternum, each forearm, and bar-center between the hands (Fig. 2) during 10 trials.

The gymnast was modeled as a mass, spring and damper system to estimate k_s and b_s from experimentally measured sternum-to-forearm distance as a function of time, $d_e(t)$ (Fig. 2). The simulated distance, $d_s(t)$, was written in terms of the solutions to the system's linear ordinary differential equations

$$d_s(t) = c_1 \sin(\omega_d t + \phi) e^{-\zeta\omega_n t} + c_2 e^{-t/\tau_2} + c_3 e^{-t/\tau_3} \tag{1}$$

where $\omega_d = \sqrt{\omega_n^2(1-\zeta^2)}$. Simulated distance parameters ω_d, $\zeta\omega_n$, $1/\tau_2$, $1/\tau_3$ are the imaginary and real parts of the system's eigenvalues. Natural frequency, ω_n, and damping ratio, ζ, characterize the damped oscillation; τ_2 and τ_3, are the characteristic times of decaying exponential functions. These function parameters, amplitudes c_1, c_2, and c_3, and phase shift, ϕ, were determined using least-squares fits of experimental data with the function $d_s(t)$.

The constants ω_n, ζ, τ_2, and τ_3 experimentally determined using the $d_s(t)$ function are equivalent to those calculated with the set of eigenvalues of the differential equations

$$\begin{aligned}(m_b + m_a)\ddot{x}_b &= -k_b x_b + k_s(x_s - x_b) + b_s(\dot{x}_s - \dot{x}_b) + (m_b + m_a)g \\ m_g \ddot{x}_s &= -k_s(x_s - x_b) - b_s(\dot{x}_s - \dot{x}_b) + m_g g\end{aligned} \tag{2}$$

Known constants are measured bar stiffness k_b, effective bar mass m_b, gymnast arm mass m_a, and remaining gymnast mass m_g. Using the characteristic equation of system (2) written in terms of the unknowns k_s and b_s

$$0 = s^4 + 0.171 b_s s^3 + (2290.555 + 0.171 k_s)s^2 + 42.574 b_s s + 42.574 k_s \tag{3}$$

values of k_s and b_s are iterated to minimize the difference between experimental and calculated eigenvalues for all 10 trials

$$F = \sum_{i=1}^{10}((\omega_n - \omega_{\mathrm{nopt}_i})^2 + (\zeta - \zeta_{\mathrm{opt}_i})^2 + (\tau_2 - \tau_{2\mathrm{opt}_i})^2 + (\tau_3 - \tau_{3\mathrm{opt}_i})^2) \tag{4}$$

Joint torque generators, with experimentally measured properties, placed at the shoulder and hips drive the forward dynamics simulation. Because these represent muscles, maximum torque was assumed to be a product of functions of joint angle θ and angular velocity ω, and torque generator activation $A(t)$

$$T = T_{\max}(\theta, \omega)A(t) \tag{5}$$

An isokinetic dynamometer (Biodex System 2) measured maximum shoulder and hip flexion and extension, and hip abduction and adduction torques as functions of θ and $\omega\cdot$ Shoulder and hip joint flexion are defined from full extension as moving the distal end of the segment in the anterior direction, and joint extensions move the distal end posteriorly. At least three maximum effort contractions were performed at each of nine concentric ($30<\omega<400^{\circ}$/s) and four