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Influence of optimization constraints in uneven parallel bar dismount swing simulations

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ABSTRACT

Forward dynamics simulations of a dismount preparation swing on the uneven parallel bars were optimized to investigate the sensitivity of dismount revolution potential to the maximum bar force before slipping, and to low-bar avoidance. All optimization constraints were classified as 1-anatomical/physiological; limiting maximum hand force on the high bar before slipping, joint ranges of motion and maximum torques, muscle activation/deactivation timing and 2-geometric; avoiding low-bar contact, and requiring minimum landing distance. The gymnast model included torso/head, arm and two leg segments connected by a planar rotating, compliant shoulder and frictionless ball-and-socket hip joints. Maximum shoulder and hip torques were measured as functions of joint angle and angular velocity. Motions were driven by scaling maximum torques by a joint torque activation function of time which approximated the average activation of all muscles crossing the joint causing extension/flexion, or adduction/abduction. Ten joint torque activation values, and bar release times were optimized to maximize dismount revolutions using the downhill simplex method. Low-bar avoidance and maximum bar-force constraints are necessary because they reduce dismount revolution potential. Compared with the no low-bar performance, optimally avoiding the low bar by piking and straddling (abducting) the hips reduces dismount revolutions by 1.8%. Using previously reported experimentally measured peak uneven bar-force values of 3.6 and 4.0 body weight (BW) as optimization constraints, 1.40 and 1.55 revolutions with the body extended and arms overhead were possible, respectively. The bar-force constraint is not active if larger than 6.9 BW, and instead performances are limited only by maximum shoulder and hip torques. Bar forces accelerate the mass center (CM) when performing muscular work to flex/extend the joints, and increase gymnast mechanical energy. Therefore, the bar-force constraint inherently limits performance by limiting the ability to do work and reducing system energy at bar release.

1. Introduction

During a swing before dismount on the women's uneven parallel bars, the timing and magnitudes of hip and shoulder joint motions influence gymnast angular velocity, mass center (CM) velocity direction and total system mechanical energy. During the swing, total system mechanical energy can be increased by using muscular work to move body segments and compensate for losses due to hand/bar friction and shoulder energy dissipation. Joint motions also store energy in the bar, transfer angular momentum between body segments, and increase angular momentum about the un-deflected bar center.

Bar swing maneuvers have been studied using inverse kinematics (Witten et al., 1996; Arampatzis and Bruggemann, 1998, 1999) and computer simulations (Yeadon and Hiley, 2000; Hiley and Yeadon, 2003, 2005, 2007). Inverse kinematic studies have identified motions that increase swing angular velocity (Witten et al., 1996), and have hypothesized that gymnasts try to maximize system energy at bar release (Arampatzis and Bruggemann, 1998). These studies have increased maneuver understanding, but are limited to analyzing previously performed techniques. Conversely, forward dynamics simulations and optimizations allow maneuver deconstruction and synthesis to understand how each joint angle change contributes to overall movement goals, and to quantify performance sensitivity to model/simulation parameters.

Constraints used in previous optimizations of women's and men's simulated swings have been based on motions observed in experimental performances in addition to gymnast anatomical and physiological limitations such as joint range of motion or strength (Hiley and Yeadon, 2003, 2005, 2007). These studies

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optimized selected swing techniques by prescribing a sequence of joint rotations during the swing and varying each motion's timing and magnitude to maximize angular momentum about the CM at bar release (Hiley and Yeadon, 2003, 2007). Although this method calculates performances that better satisfy objective function criteria, it assumes that current techniques are close to optimal and does not allow for discovery of alternative, possibly very different techniques.

A true maximal performance can be identified if simulated swing optimizations are constrained using only gymnast anatomical/physiological limitations of flexibility, strength and speed, and geometric constraints of low-bar avoidance and minimum landing distance. If calculated and observed performances vary significantly using minimal constraints, more can be learned about missing model attributes, motion objectives and constraints.

Most simulations investigate men's horizontal bar rather than women's uneven parallel bars, and no simulations have been unconstrained enough to investigate optimal low-bar avoidance strategies or have quantified the resulting performance decreases due to the additional shoulder and hip motions. Typical low-bar avoidance techniques include hip pike and/or straddle (leg abduction) and shoulder extension, or hip hyperextension and shoulder hyperflexion (Fig. 1).

The uneven bar forces that result in a gymnast slipping from the bar have also not been studied, even though slipping occasionally happens (Moceanu, 1995). Reported peak experimental uneven-bar forces have been between 3.6 and 4.0 body weight (BW) for skilled gymnasts (Hay et al., 1979; Witten et al., 1996; Sheets and Hubbard, 2008) even though bar stiffnesses have changed with new materials, and maneuver angular velocities have increased. Peak reported values for the giant swing on the men's horizontal bar are 4.5 BW, although this value may be conservative because swings using only one arm can be performed (Neal et al., 1995).

This paper's goal is to optimize forward dynamics simulations of a dismount preparation swing to investigate the effect of low-bar avoidance and maximum bar-force constraints on dismount rotation potential. By including different constraints while optimizing simulated swing performances to maximize dismount rotation potential, it is possible to determine the performance sensitivity to each constraint. While all anatomical/physiological and geometric constraints were included in the simulations, only the dismount rotation potential's sensitivity to the bar-force and low-bar avoidance constraints were investigated. Including appropriate constraints is essential for calculating realistic performances using computer simulation.

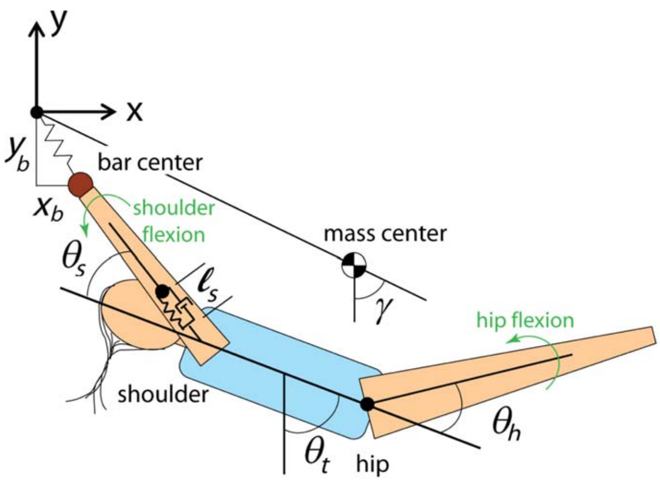

Fig. 1. Schematic of the compliant shoulder, gymnast model.

2. Methods

Forward dynamics simulations of a dismount preparation swing on the uneven parallel bars were optimized to investigate the sensitivity of dismount rotation potential to the constraints of low-bar avoidance, and maximum bar force before slipping. The subject-specific female gymnast and compliant uneven bar models' ability to simulate an experimentally measured swing have been previously evaluated (Sheets and Hubbard, 2008). While the optimization methods used in Sheets and Hubbard (2008) and this paper are similar, this paper's objective function calculated an optimal swing to maximize dismount revolution potential while the previous paper's objective function minimized differences between a simulated and experimental swing performance.

The seven degree-of-freedom gymnast model has four segments: a torso/head, arm and two legs (Fig. 1). In a deduction-free performance, hip and shoulder joints can rotate but elbows and knees cannot bend. Body segment parameters including moments of inertia, masses and CM locations were estimated with Yeadon's inertia model which uses 95 measurements (1990, Table 1). The hips are frictionless ball-and-socket joints and the arm can only move in the sagittal plane. During the swing, arm translation with respect to the torso in the sagittal plane is most likely caused by humeral motion with respect to the glenoid cavity, but may also include translations of the glenoid in the sagittal plane. A parallel spring ($k_s = 41{,}730$ N/m) and damper ($b_s = 5573$ N s/m) model the compliant shoulder. Its properties were estimated by matching a simulated and experimental swing performance (Sheets and Hubbard, 2008). Optimal performances were constrained by anatomical joint range of motion limits, but the calculated performances did not approach these boundaries.

The bar model is a massless, linearly elastic spring with stiffness 16,860 N/m, and measured coefficient of friction between the concentric hand and 0.02 m radius bar of $\mu = 0.85$ (Sheets and Hubbard, 2008). Bar damping is not included because the shoulder accounts for most of the system damping (Hiley and Yeadon, 2005).

The forward dynamics simulation motion is driven by joint torque generators at the gymnast model's shoulder and hip. Each maximum torque was assumed to be a product of functions of joint angle θ and angular velocity ω, and torque generator activation because the generators represent muscles.

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

Each of the flexion and extension (abduction/adduction) joint torque generator's properties were experimentally measured using an isokinetic dynamometer (Biodex System 2) and a surface was fit to the data (Fig. 2; Sheets and Hubbard, 2008).

$$T(\theta, \omega) = \frac{(a + be^{p\omega})}{(1 + ce^{p\omega})(1 + de^{p\omega})}(x_1\theta^2 + x_2\theta + x_3) \tag{2}$$

The downhill simplex method (Nelder and Mead, 1965) calculated coefficients a, b, c, d, p, q, x_1, x_2 and x_3 that minimized the sum of mean absolute differences between experimental and predicted torques for all n data samples collected during nine concentric and 4 eccentric angular velocity trials ($i = 13$).

$$J = \sum_{i=1}^{13}\left(\sum_{j=1}^{n} |T_e(\theta_j, \omega_i) - T_p(\theta_j, \omega_i))|/n\right) \tag{3}$$

Surface ω dependence is a double hyperbolic curve with plateaus at large eccentric and concentric ω (King and Yeadon, 2002), and θ dependence is parabolic. Activation dependence is not included because maximal effort was exerted during each trial. Torque is assumed to be zero if extrapolated torque is negative ($T(\theta,\omega)<0$).

Arm and leg motions during the swing are calculated by scaling maximum instantaneous joint torques by joint torque activation, $A(t)$ (Cheng and Hubbard, 2005). The scalar function of time, $A(t)$, varies over [−1, +1] and is the percentage of the maximum possible torque produced by fully activating all muscles crossing each joint at the current state causing joint extension/flexion (or abduction/adduction), respectively. Because muscular activation cannot change instantaneously, the joint torque activation rate of change was limited to be less than 1/(80 ms). This rise time of 80 ms is slightly smaller than experimental joint moment rise times during human vertical jumping of 90–112 ms (Bobbert and van Zandwijk, 1999).

Rather than specifying activations at all times throughout the maneuver, a vector represents $A(t)$ at the beginning of each interval (node), and cubic splines approximate activation between nodes (Cheng and Hubbard, 2005). There must be enough nodes to reproduce complexities of the motion, but as few as possible to provide computational efficiency.

Dismount revolutions were maximized by optimizing 30 nodal joint torque activation control variables and the bar release time using the downhill simplex method (Nelder and Mead, 1965). Swing motion was described by nonlinear