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RESEARCH NOTE

Effect of hip flexibility on optimal stalder performances on high bar.

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Abstract

In the optimization of sports movements using computer simulation models, the joint actuators must be constrained in order to obtain realistic results. In models of a gymnast, the main constraint used in previous studies was maximum voluntary active joint torque. In the *stalder*, gymnasts reach their maximal hip flexion under the bar. The purpose of this study was to introduce a model of passive torque to assess the effect of the gymnast's flexibility on the technique of the straddled stalder. A three-dimensional kinematics driven simulation model was developed. The kinematics of the shoulder flexion, hip flexion and hip abduction were optimized to minimize torques for four hip flexion flexibilities: 100°, 110°, 120° and 130°. With decreased flexibility, the piked posture period is shorter and occurs later. Moreover the peaks of shoulder and hip torques increase. Gymnasts with low hip flexibility need to be stronger to achieve a stalder; hip flexibility should be considered by coaches before teaching this skill.

Keywords: simulation, gymnastics, coordination, passive torque

Introduction

A high bar routine in men's artistic gymnastics consists of a number of circling skills, release and regrasp skills, and a dismount. Previous biomechanical analyses have focused on the transfer of energy between the gymnast and the bar (Arampatzis & Brüggemann, 1998; 2001) or on the technique of the giant circles on high bar and asymmetrical bars based on a six degrees of freedom (DoF) planar computer simulation model (Hiley & Yeadon, 2003ab; 2005ab; 2007). The studies investigated the ability to generate angular momentum (Hiley & Yeadon, 2003a; 2005a), the margin of error for dismounts (Hiley & Yeadon, 2003b; 2005b) or the consistency of release and regrasp skills (Hiley et al., 2007).

Among the circling skills there are elements in which the gymnast moves close to the bar such as *endo* (free circle forward) and *stalder* (free circle backward, Figure 1). The gymnast swings to handstand with a piked posture as he passes through the lower part of the circle. The basic technique of the stalder (Figure 1) comprises a "*closing phase*" (b-c) reaching the fully piked posture (d-e) with legs between the bar and the shoulders. The fully closed posture may either be piked (legs together) or straddled (legs apart) and is held for a period before extending to handstand: "*opening phase*" (f).

Figure 1: Stalder from handstand to handstand.

Due to changes in the FIG (Fédération Internationale Gymnastique) Code of Points (FIG, 2006), these skills have recently increased in popularity with additional difficulty points available for adding longitudinal turns during the *opening phase*. However the element must always be completed in a nominal handstand (within $\pm 15^\circ$ of the vertical). Such elements can be linked by giant circles or linked directly together without additional swings. Inter-segmental coordination and flexibility seem to be the main qualities required to perform this movement (Pedescu, 1985). There exist various techniques according to the physical qualities of the gymnast.

Due to gravity and centrifugal effects, the gymnast reaches maximal hip flexion under the bar. The stretching of soft tissue (muscles, tendons and ligaments) crossing the hip joint generates passive joint moments – τ_p – that are not negligible (Hoang et al., 2005). This component of joint torque has not been introduced in previous models of high bar simulation. Since the giant circle performance depends mainly on coordination and the ability to produce large joint torques, complex models of maximum voluntary active joint torque – τ_A – have been developed (Yeadon et al., 2006) and then introduced into optimization procedures to obtain realistic movements.

In the case of movements reaching the joint end-range of motion, the utilization of a passive torque model is essential. Exponential models of passive moment-angle relationships (Yoon and Mansour, 1982; Davy and Audu, 1987; Hoang et al., 2005) have previously been used to capture the sharp increase in force that occurs near the end-range of motion. This paper investigates the optimization of straddled stalder from handstand to handstand for different gymnast flexibilities. The purpose is to determine the change in coordination with decreasing hip flexibility.

Methods

A combination of experimental and theoretical approaches was used. Video data were collected on an elite gymnast performing straddled stalders from handstand to handstand. The kinematics was reconstructed using a chain model presented in Begon et al. (2008) combined with an optimization procedure. Based on this chain model, the computer simulation model was simplified by introducing damped springs and coupling motions; the shoulder translation is expressed as a function of its flexion and the back flexion depends on the hip flexion and abduction. Finally, the simulation model was used to optimize the performance in the stalder for four different hip flexibilities based on the integral quadratic amount of active torques.

Data collection and analysis

The participant, a member of the Great Britain Men's Senior Gymnastics Squad (17 years old, 61.6 kg, 1.705 m), gave informed consent to perform setup movements (to estimate the parameters of a personalized chain model) and also a number of stalders varying in technique and speed from trial to trial according to specific instructions. The gymnast was linked to the bar using loops and gloves to minimize the friction with the bar. A set of 95 anthropometric measurements were taken on the gymnast and inertia parameters were estimated using the model of Yeadon (1990). Five successful stalders (*i.e.* to handstand) were selected to give a range of technique (Figure 2).

Figure 2: Graphical sequences of the five actual stalders from handstand to handstand with specific instructions: [A] self-selected technique, [B] pike later, [C] as slow as possible, [D] start with shoulder flexion, [E] as fast as possible.

All trials were captured using an automatic 18 camera system (VICON Motion Capture Systems, Oxford, England) operating at 100 Hz in a 3x5x5 m calibrated volume centred on the high bar. A six-parameter, three-dimensional, 12 DoF model was used to describe the kinematics of the straddled stalder (Begon et al., 2008; Figure 3A). Ten 25 mm diameter spherical markers were attached to the left side of the body at the lateral malleolus, tibia, lateral knee, lateral side of mid-thigh, left anterosuperior and posterosuperior iliac spines, xiphoid, first thoracic vertebra, olecranon, ulnar styloid plus two markers to locate the middle of the bar. Markers were added to estimate the location of left ankle, knee and wrist joint centres (medial malleolus, medial femoral condyle and radial styloid) as midpoints and to functionally determine the left hip and shoulder joint centres (right anterosuperior and posterosuperior iliac spines, manubrium, a rigid tripod fixed

on the left acromion, under the left deltoid and medial side of the left elbow) using the SCoRE algorithm (Ehrig et al., 2008). The model was considered to be symmetrical about the sagittal plane. The 12 generalised coordinates were optimized for each frame by means of a Newton-Gauss nonlinear least squares algorithm under the *HuMAnS* toolbox (Wieber et al., 2006).

Figure 3: [A] Model definition with the degrees of freedom and the parameters. Degrees of freedom: q_{1-3} translation of the bar, q_4 arm rotation, q_5 body translation, q_6 arm lengthening, q_7 shoulder flexion, q_8 spinal flexion, q_9 thigh flexion, q_{10} thigh abduction, q_{11} thigh torsion and q_{12} knee flexion. Parameters: p_1 arm length, p_2 torso length, p_3 half-width of the pelvis, p_4 pelvis height, p_5 knee adduction and p_6 thigh length. [B] Simplified model for the simulation with damped springs (q_s), coupling motion ($f(q)$) and set coordinates (k).

Simulation Model

The 12 DoF in the data analysis model were reduced by introducing damped springs, coupling motions and some assumptions for the simulation model (Figure 3B). The displacement of the bar in the sagittal plane (q_{s1}, q_{s2}) and the gymnast's shoulder structure (q_{s6}) were modelled as damped linear springs (stiffness s and damping coefficient c). The model parameters were adjusted using a matching procedure detailed in the next section. An analysis of back flexion (q_8) and thigh torsion (q_{11}) was carried out and showed relationships with hip flexion and abduction (q_{9-10}). Back flexion and thigh torsion were then expressed as polynomial functions: $f_8(q_9, q_{10})$ and $f_{11}(q_9, q_{10})$. There was also a parameter $f(q_7)$ that governed the elevation of the scapular girdle as a function of the shoulder flexion angle (q_7) to avoid singularity with q_6 when the arm and the trunk are aligned, and to obtain a realistic translation of the glenohumeral joint centre while flexing the arm. The assumptions were that the bar only had displacement in the sagittal plane ($q_3(t)=k_3=0$), the gymnast did not translate along the bar ($q_5(t)=k_5=0$) and the knees remained slightly flexed ($q_{12}(t)=k_{12}=5^\circ$) throughout the movement, as measured in average for the actual movements.

In this seven DoF ($q_{s1, s2, 4, s6, 7, 9, 10}$) simulation model, the controlling DoF were the shoulder flexion-extension (q_7), the hip flexion-extension (q_9) and the hip abduction-adduction (q_{10}) while the bar (q_{s1} and q_{s2}) and the arm lengthening (q_{s6}) were modelled as damped springs. Finally the

arm rotation relative to the bar (q_4) could be solved from the equation of motion which was expressed as an Euler-Lagrange equation:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{N}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) = \boldsymbol{\tau}, \quad [1]$$

where $\mathbf{M}(\mathbf{q})$ is the inertia matrix and $\mathbf{q}=[q_1, \dots, q_{12}]^T$ represents the generalized coordinates. The Coriolis and centrifugal effects are grouped together in $\mathbf{N}(\mathbf{q}, \dot{\mathbf{q}})$; $\mathbf{G}(\mathbf{q})$ is the gravity effect and $\boldsymbol{\tau}$, with $\boldsymbol{\tau} = \boldsymbol{\tau}_A + \boldsymbol{\tau}_P$, represents the generalized forces comprising the horizontal and vertical forces applied to the bar, the friction between the bar and the hands (considered equal to zero), the force at the arm lengthening spring, and the joint torques generated by the shoulders in flexion/extension and the hip in flexion/extension and abduction/adduction. The variable $\mathbf{q}$ that describes the configuration of the system consists of two different sets: a first set $\mathbf{q}1$ describing the bar position, the arm rotation and the arm lengthening that are unknown kinematics. A second set $\mathbf{q}2$ describes the joint angles of the gymnast that are the input of the model. Hence the Lagrangian dynamics (Eq. [1]) becomes:

$$\begin{bmatrix} \mathbf{M}_{11} & \mathbf{M}_{12} \\ \mathbf{M}_{21} & \mathbf{M}_{22} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}1 \\ \ddot{\mathbf{q}}2 \end{bmatrix} + \begin{bmatrix} \mathbf{N}_1 + \mathbf{G}_1 \\ \mathbf{N}_2 + \mathbf{G}_2 \end{bmatrix} = \begin{bmatrix} \boldsymbol{\tau}1 \\ \boldsymbol{\tau}2 \end{bmatrix} \quad [2]$$

As $\ddot{\mathbf{q}}2$ is calculated as the second time derivative of quintic functions and $\boldsymbol{\tau}1$ depends on $\mathbf{q}1$ and $\dot{\mathbf{q}}1$ ($\boldsymbol{\tau}1 = [-s_1 q_{s1} - c_1 \dot{q}_{s1} \quad -s_2 q_{s2} - c_2 \dot{q}_{s2} \quad 0 \quad -s_6 q_{s6} - c_6 \dot{q}_{s6}]^T$), $\ddot{\mathbf{q}}1$ is solved by:

$$\ddot{\mathbf{q}}1 = \mathbf{M}_{11}^{-1}(\boldsymbol{\tau}1 - \mathbf{N}_1 - \mathbf{G}_1 - \mathbf{M}_{12} \ddot{\mathbf{q}}2) \quad [3]$$

Parameters of the simulation model were the segmental inertia parameters, the stiffness $s_{1,2,6}$ and damping $c_{1,2,6}$ coefficients of the bar and shoulder springs. Input to the simulation model comprised the initial state of the bar and the shoulder ($q_1^i, q_2^i, q_6^i, \dot{q}_1^i, \dot{q}_2^i, \dot{q}_6^i$), the initial angular position and velocity of the arm ($q_4^i, \dot{q}_4^i$) and the joint angle time histories ($q_{7,9,10}^{t_i \rightarrow t_f}$) expressed as sequences of quintic functions in order to evaluate the first and second time derivatives. Output from the simulation comprised the time histories of the bar displacements and the arm rotation angle. The whole body rotation angle ϕ was calculated as the angle between the upward vertical and the line joining the neutral bar position to the mass centre. Then joint torques, potential and kinetic energies were calculated.

Matching Simulations

For the model parameters optimization, quintic splines were used to fit the time histories of the recorded generalized coordinates. The simulation model was implemented with a genetic optimization algorithm (Caroll, 1996). A cost function was established to minimise the root mean square difference (tilde notation represents the square difference) between the recorded and simulated performances described by the bar displacement q_{1-2} , the arm rotation q_4 and arm lengthening q_6 . The kinematics of the five stalders were considered together:

$$F = \sqrt{\frac{1}{5} \sum_{s=1}^5 \frac{1}{n} \sum_{t=0}^n w_1 \tilde{q}_1 + w_2 \tilde{q}_2 + w_4 \tilde{q}_4 + w_6 \tilde{q}_6}, \quad [4]$$

The weightings, w_i , were chosen so that each component of the cost function made approximately equal contributions based on the analysis of the actual performances. The following parameters were allowed to vary in order to improve the match between the recorded and

simulated performances. The stiffness and damping coefficients of the bar were allowed to vary between 20,000 and 27,500 Nm⁻¹ and between 0 and 500 Nsm⁻¹ to conform to the specifications of the FIG (2006). The stiffness and damping coefficients of the arm lengthening spring were allowed to vary over wider ranges (10,000-20,000 Nm⁻¹ and 500-2000 Nsm⁻¹) than those of the bar springs. In line with the accuracy of the model of Yeadon (1990), the segmental masses (for segments 1-2 & 5-7, referred to Figure 3) and moments of inertia (for segments 2 & 4-7) were allowed to vary between $\pm 8\%$ and $\pm 10\%$ (1% error in measurement for each dimension to calculate the volume and 5% error in density estimation) respectively, while the total body mass was constrained to remain at its measured value. These bounds were not reached in the matching optimization.

Optimization

The stalder was modelled with series of five polynomial functions for the shoulder flexion/extension, four for hip flexion/extension and five for the hip abduction/adduction, that were characterized by their duration ($\mathbf{D}_i$) and final angle magnitude ($\mathbf{Q}_i$). These numbers were sufficient to match the recorded kinematics with a maximum RMS error of 5° (for a total range of motion of 110°), 4° (165°) and 3° (70°) for the shoulder flexion, hip flexion and abduction, respectively. During each part (except for the first part for the hip abduction) the joint angles (q_7, q_9, q_{10}) were allowed to change independently. In changing a joint angle q from q_i to q_j between times t_i and t_j , the time history was given by a quintic function that fits well gymnast kinematics on high bar (Yeadon & Hiley, 2000): $q(x) = q_i + (q_j - q_i)u(x)$ where $u(x) = x^3(6x^2 - 15x + 10)$ with $x = (t - t_i)/(t_j - t_i)$ so that $\dot{q} = \ddot{q} = 0$ at t_i and t_j . A genetic algorithm (Caroll, 1996) was used to manipulate the phase durations and the extreme joint angles of the shoulder and the hip in order to minimize the cost function, the integral quadratic amount of active torques throughout the motion:

$$J = \int_{t_i}^{t_f} \frac{1}{2} \boldsymbol{\tau}_A(t)^T \mathbf{W} \boldsymbol{\tau}_A(t) dt, \quad [5]$$

where $\mathbf{W}$ is a weighting matrix defined from actual performances and $\boldsymbol{\tau}_A$ the active generalised forces. The cost function is subject to the system dynamics $\dot{\mathbf{x}} = f(t, \mathbf{x}, \boldsymbol{\tau})$, where $\mathbf{x} = [\mathbf{q}, \dot{\mathbf{q}}]^T$ is the state vector of the system, under constraints:

$$\begin{cases} \theta_i(t_i, \mathbf{x}_i) = 0 \\ \theta_f(t_f, \mathbf{x}_f) \leq 0 \\ h(t, \mathbf{x}) \leq 0 \\ g(t, \mathbf{x}, \boldsymbol{\tau}_A) \leq 0. \end{cases} \quad [6]$$

The initial state was prescribed (θ_i) and at the final rotation angle, greater than 365°, the hip and shoulder angles had to be less than 5° (θ_f final state). These values were chosen to lie within the FIG (2006) rules. An additional path constraint $h(t, \mathbf{x})$ was imposed to obtain a piked straddled posture (i.e. legs apart and lower than the bar in the arms local frame) under the bar and to avoid any body collision (lower limbs relative to the trunk, upper limbs or bar). The control constraint $g(t, \mathbf{x}, \boldsymbol{\tau})$ was used to ensure that the generalized forces did not exceed the gymnast's strength.

Active and passive torques

The joint torque at the shoulder and the hip was the sum of the passive and active torques. Since the knee remained slightly flexed, a double exponential model (Hoang et al., 2005; Silder et al., 2007) defined the passive torque such that the torque magnitude was equal to an arbitrary value of

100 Nm at a desired end-range of motion (100 Nm of flexor torque at maximal extension $q^{\min}$, and 100 Nm of extensor torque at maximum flexion $q^{\max}$):

$$\begin{cases} \tau_p(q) = B_1 \exp^{k_1 q} + B_2 \exp^{k_2 q} \\ \tau_p(q^{\min}) = 100 \text{ Nm} \\ \tau_p(q^{\max}) = -100 \text{ Nm.} \end{cases} \quad [7]$$

The arbitrary value was chosen after measurements on an isokinetic dynamometer. This function represents the net passive torque due to muscle stretching and other structures (e.g. soft connective tissue loads and ligament forces). Due to gravitational and centrifugal effects, the passive hip extensor torque could exceed -100 Nm slightly and the hip flexion angle could exceed the hip flexion limit by a few degrees. The maximum active torque was defined as a function of joint angle and angular velocity: $\tau_A^{\max} = f(q, \dot{q})$ for the shoulder and the hip (Yeadon et al., 2006; King et al., 2006). Since it was not possible to collect data on isokinetic ergometer with this gymnast, the model of another gymnast was scaled in order to respect the joint torques calculated using the stalder experimental. The kinematics was optimized for four hip flexion flexibilities $q_g^{\max}$: 100°, 110°, 120° and 130°. From times histories and key values of kinematics (time at mass centre-bar angle $\varphi = \{90^\circ, 180^\circ, 270^\circ, 360^\circ\}$, straddled pike period, maximum hip flexion and abduction), kinetics (shoulder and hip torque under the bar) and energy (potential, kinetic – $E_k = \frac{1}{2} \mathbf{q}^T \mathbf{M}(\mathbf{q}) \mathbf{q}$ – and total), the changes in technique with a decrease in flexibility were assessed.

Results

For five recorded stalders (Eq.[4]), the stiffness coefficients of the bar obtained in the matching procedure were 20,024 and 20,007 Nm⁻¹ for the horizontal and vertical bar displacements respectively, which lay within the limits as set out by the FIG (2006). The damping coefficients were also close, 499 *versus* 498 Nsm⁻¹. The parameters for the arm lengthening (q_{s6}) had a stiffness of 12,000 Nm⁻¹ and a damping coefficient of 1,473 Nsm⁻¹.

For each of the four values of hip flexibility, an optimum movement which minimized the cost function (Eq. [5]) while respecting the constraints (Eq. [6]) was found; the stalders were performed with a straddled piked posture under the bar to reach a nominal handstand without body collisions (Figure 4). As the flexibility decreased, the scores J in Eq. [5] (and hence the active joint torques) increased. In general, the kinematics and the kinetics of the four flexibility conditions were similar while the energy time history of the 100° flexibility condition differed from the other conditions. In the actual stalders (Figure 2) compared to all of the optimized movements, the gymnast attained the piked posture later, began the shoulder opening earlier and had greater hip flexion under the bar.

Figure 4: Optimum performances of stalder for four hip flexibilities: 130°, 120°, 110° and 100°.

Note: the path of the centre of mass (dashed line) and the sector where the gymnast is in a piked posture (filled with solid diamond) with the maximum hip flexion (bold line) give additional information about the kinematics.

Table 1: Key values for the optimum stalder for four hip flexibilities

Stalder	130°	120°	110°	100°
Score	100%	101%	101%	105%
piked posture [duration]	34-285° [0.93 s]	38-283° [0.89 s]	41-282° [0.86 s]	62-293° [0.73 s]
time at $\varphi=90^\circ$	1.32 s	1.32 s	1.34 s	1.28 s
$\varphi=180^\circ$	1.61 s	1.61 s	1.63 s	1.53 s
$\varphi=270^\circ$	1.94 s	1.94 s	1.95 s	1.82 s
$\varphi=360^\circ$	2.60 s	2.57 s	2.54 s	2.60 s
max q_9	121° ($\varphi=143^\circ$)	118° ($\varphi=144^\circ$)	112° ($\varphi=137^\circ$)	99° ($\varphi=167^\circ$)
max q_{10} at $\varphi=180^\circ$	29° $\tau_2=2422$ N $q_7=70^\circ$, $\tau_7=274$ Nm $q_9=121^\circ$, $\tau_9=-60$ Nm	36° $\tau_2=2443$ N $q_7=70^\circ$, $\tau_7=287$ Nm $q_9=118^\circ$, $\tau_9=-16$ Nm	36° $\tau_2=2414$ N $q_7=71^\circ$, $\tau_7=311$ Nm $q_9=111^\circ$, $\tau_9=35$ Nm	40° $\tau_2=2634$ N $q_7=97^\circ$, $\tau_7=317$ Nm $q_9=99^\circ$, $\tau_9=-18$ Nm

The total duration of the stalders ranged from 2.54 to 2.60 s. The timing (time at 90°, 180°, 270° and 360° of rotation) was not really affected by gymnast flexibility; only at 100° the gymnast was slightly faster from $\varphi=0^\circ$ to 180° and slower in the fourth quadrant. With decreasing flexibility, the piked posture started later (34° to 62°) and its duration diminished (Table 1). In all the flexibility conditions the pike was maintained at least until 280° (282-293°). Under the bar, the postures differed slightly, the shoulder angle and hip abduction angle increased with decreased hip

flexion. These changes in posture minimize the effects of the centrifugal force and gravity on the active joint torques by the contribution of the hip passive torque. For the four optimized stalders, the maximum value of the hip flexion (121° , 118° , 112° , 99° for 130° , 120° , 110° and 100° flexibilities) was close to the value which corresponded to a passive torque of -100 Nm and only exceeded this for the 110° flexibility performance.

The kinetics was also affected by the hip flexibility (Figure 5). The vertical force applied to the bar exceeded 2400 N for 110 - 130° flexibility and 2600 N at 100° flexibility, *i.e.* more than four body weights. In general, the gymnast produced an eccentric shoulder flexor torque from $\varphi = 0^\circ$ to 80° followed by an extensor torque until 280° and then a flexor torque again to reach handstand. The maximum shoulder extensor torque value always occurred under the bar and increased with decreased flexibility. The maximum shoulder flexor torque values (at the beginning and before handstand) also showed an upward trend from 130° to 100° hip flexibilities.

Figure 5: Time histories of the kinematics (q_9) and kinetics (total torque τ_9^{A+B} and active torque τ_9^A) of the hip flexion-extension. Time histories of the shoulder angle (q_7) and active torque (τ_7).

Note: Vertical dashed lines represent the body rotation φ at 90° , 180° , 270° and 360° .

A peak hip flexor torque generally appeared just before 90° of body rotation and a peak hip extensor torque before reaching handstand. However the magnitude of the first peak and the

kinetics from $\varphi=90^\circ$ to 270° changed markedly with flexibility. As with shoulder torque, peaks of hip flexion joint torque increased with decreased flexibility (62, 77, 95 and 141 Nm, from 130° to 100° flexibility). In the 130° flexibility condition the average joint torque while the gymnast was below the horizontal ($90^\circ < \varphi < 270^\circ$) was -34 Nm (mainly hip extensor torque); this value became zero in the 120° flexibility condition and then positive (31 and 20 Nm) in 110° and 100° conditions. In the four cases, the total energy (Figure 6) decreased sharply at the beginning of the movement, stayed nearly constant until $\varphi=90^\circ$ before decreasing again until 180° . After the body passed through the lower part of the circle, the energy increased slowly and then faster ($\varphi > 330^\circ$), especially for 100° hip flexibility. The potential and kinetic energies from 110° to 130° flexibilities were similar while the change in energy for the 100° flexibility was smaller mainly due to the potential energy.

Figure 6: Kinetic (E_k), potential (E_p) and total (E_k+E_p) energies for the four as functions of the body rotation φ .

Discussion

This study has shown that for a wide range of hip flexibility (100 - 130°) gymnasts can perform a straddled staldar from handstand to handstand with a decreased least torque norm by modifying the coordination. A flexible gymnast minimizes the peaks of hip and shoulder torques by piking earlier and having greater shoulder flexion. The early piking decreases the potential energy and results in a smaller centrifugal force under the bar. For a stiff gymnast, the centrifugal forces allow the piked

posture to be maintained under the bar, moreover the hip abduction increased. In all the flexibility conditions, the performance is partially a balance between gravitational and centrifugal effects and the torque generated by the passive structures of the musculoskeletal system.

Scaling the maximum joint torques using the dynamics of actual stalders was an adequate method in regard to the chosen cost function. In order to optimize the performance of an elite gymnast a subject-specific data collection on an isokinetic ergometer would be necessary to obtain realistic results. The previous gymnast models for high bar movements (Hiley and Yeadon, 2003-2007) have been adapted to the stalder specific dynamics by introducing a passive torque model, an extra DoF between the torso and the pelvis and by coupling motions (personalised behaviour of the scapular girdle elevation as a function of arm flexion as well as back flexion and hip torsion as functions of hip flexion and abduction which allowed realistic kinematics without increasing DoF. Since the purpose was to compare optimum stalders for different hip flexibilities, the arbitrary value of 100 Nm was not a limit of our study. However for other purposes — performance optimization and analysis of mechanical work (Silder et al., 2008) or muscular force estimation for actual performances (Vigouroux et al., 2006) —, a subject-specific model would be important. The passive torque model could be improved by considering both hip flexion and abduction using an isokinetic dynamometer and electromyography.

The hip active torque under the bar is small (e.g. at 120° flexibility condition) and so the majority of the torque is passive. This result is consistent with practice in that gymnasts do not feel they produce large hip torques to maintain the pike. From a coaching point of view, the most difficult to learn is the control of the angular velocity in the first part and then the balance under the bar to avoid an early body opening. However the accuracy of the model is difficult to experimentally assess because an active torque due to stretching reflex is added to the passive torque. This simulation model will be appropriate for studying and optimizing other gymnastics skills with straddled legs (e.g. endo and lift to handstand) or with large hip and back flexion (e.g. dislocation on high bar and swings on parallel bars for double piked somersault dismounts).

The stalders were obtained using a global genetic optimization in a large solution space. The discretization of the parameters (128 bit binary encoding, *i.e.* a minimum resolution of 0.008 s and 1°) was sufficient in line with the work of Hiley and Yeadon (2007) on the coordination robustness on high bar. For a flexibility of 130°-120°, the algorithm was rapid in finding a solution which respected the constraints while the space of possible solutions became smaller for a stiffer gymnast. The algorithm did not find a feasible solution for a flexibility less than 100° because the torque, required to attain the piked posture, exceeded the gymnast's strength or there were collisions of the legs with the bar. An approach based on the coordination robustness (Hiley and Yeadon, 2007) by introducing error in the time of the “closing phase” could bring additional information on the stiff gymnast's ability to perform the stalder consistently.

While only three DoF were controlled, the comparison of the four flexibility conditions remains difficult because the movement is subject to important centrifugal and gravitational effects which can compensate for each other or can be compensated for by the passive torque. Hence, there may exist several local minima which make the global optimization difficult. In general, from 110° to 130°, the change in flexibility does not penalize the gymnast and small compensations occur. For a 100° hip flexion flexibility, the coordination is more affected. To simplify the discussion of results, movement can be divided into three phases: [1] from handstand to the piked posture, [2] swing in a piked posture and [3] opening phase to complete stalder to handstand. As we have chosen a least squared force criterion, the mechanical aim of each phase is [1] to minimize the energy of the system (decrease the potential energy to minimize the joint torques

under the bar but also to reach handstand), [2] to optimize the piked posture under the bar (balance between inertial and gravitational effects and passive hip torque in relation to gymnast's flexibility) and [3] to control the lift to handstand with a small amount of kinetic energy.

During the *first phase* of the stalker, the total energy decreases with a slow and large hip flexion and a small shoulder extension. This movement requires eccentric contraction for both hip and shoulder joints. The beginning of the piked posture occurs progressively later with decreased flexibility but the mechanical energies are similar at this instant for the four flexibility conditions. In competition, the gymnast can either use this technique or begin the stalker with a large shoulder extension to be able to increase the kinetic energy with a large and fast hip flexion. In general for elite gymnasts, the piked posture begins later – the centre of gravity remaining far from the bar (Figure 2) – in order to produce a greater amount of energy. Hence gymnasts have a larger margin of error in the *third phase* of the movement to complete the movement without deviation or to perform longitudinal turns before handstand. This strategy explains the main differences between actual and simulated performances. Since the angular velocity under the bar is greater in actual performances, the passive structures are more extended and gymnasts reach a greater hip flexion.

In the *second phase*, the shoulder angle and hip abduction angle compensate for the hip flexion. These angle adjustments are small (less than 10°) between 110° and 130° of hip flexibility but have consequences for the hip kinetics. In the 120° flexibility condition, the piked posture requires only low active torques (on average equal to zero) because the passive torque compensates for gravitational and inertial effects. In contrast to this balanced condition, the 110° flexible gymnast has to generate a hip flexor torque to maintain the posture and the 130° flexible gymnast an extensor torque to avoid an over-inverted posture. Greater hip flexion for reducing the active hip extensor torque would require more shoulder flexion but the shoulder is weak at this angle in relation to the strength model. This kind of coordination is nevertheless possible for female gymnasts who are very flexible at the hips but cannot produce large shoulder torques. In this case, stalkers are performed with the arms aligned with the trunk and a hip plus back flexion higher than 180° that would cause smaller shoulder torques. Future optimizations using a joint torque model specific to female gymnast should support this statement.

In the 100° flexibility condition, the moment of inertia about the bar is smaller and creates a faster rotation and a higher kinetic energy. In the *third phase*, large shoulder and hip torques (opening actions) are required to reach handstand since the angular velocity is small, the fourth quadrant is made in 0.6 to 0.7 s. The centre of mass paths (Figure 4) show that this *third phase* is mainly a vertical displacement and requires balance control. The optimized solutions minimize the integral quadratic amount of active torques and differ from the actual movements of the elite gymnast. However the optimized simulations are similar to the techniques used by novice gymnasts when learning stalker. In the performances by the elite gymnast (Figure 2 A, B, E) the arms are aligned with the trunk in the fourth quadrant, unlike the optimized simulations. This may be because it facilitates the performance of longitudinal turns. Thus unlike the novice gymnasts who may indeed minimize joint torque, there are other considerations which influence the technique used by elite gymnasts. Future simulations will be carried out to maximize angular momentum or minimize joint torque in the fourth quadrant of rotation to find the stalker technique which would be the most suitable for gymnast progression.

To summarise, the hip flexion flexibility has an effect on the dynamics of straddled stalker from handstand to handstand. From 110° to 130° hip flexibility, the kinematics are similar and the peak shoulder and hip torques increase with decreased flexibility. For a 100° hip flexibility, there

are larger compensations between the hip and shoulder angles. The movement requires higher torques to reach the piked posture and to complete the staldler to handstand. Greater flexibility results in less physical demand on the gymnast.

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