

## A Feedback Controller Design for a Biomechanical Model of the Press Handstand in Gymnastics

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The purpose of this study was to design a PID based control system for a biomechanical model of the press handstand in gymnastics. The model was utilized to simulate a press handstand performance of a gymnast. A total of 10 simulations were performed using different controller parameters to achieve a decent result in joint kinematics which matches with the actual performance. The results of this study showed that maximum and minimum torque values can be used as proportional gain of a P controller. This PID based feedback control model can be developed and used for classification of the control parameters among press handstands performed on different apparatuses such as rings and parallel bars in gymnastics.

**KEYWORDS:** gymnastics, press handstand, feedback, control, modelling

**INTRODUCTION:** The press handstand is a basic non-acrobatic element which is often used in the floor routines in gymnastics. The body configuration between the initial and the final position is adjusted mainly by the muscular torques acting at the wrist, shoulder, and hip joints (Prassas, 1988) which are often called as hip and wrist (or shoulder) strategies (Yeadon and Trewartha, 2003; Kerwin and Trewartha, 2001) of a hand balance. Human body, as a dynamic system, is stabilized using various feedback mechanisms (Gautier et al. 2007) which provide neuromuscular control of the movement (Enoka, 2008). In robotics, Proportional-Integral-Derivative (PID) controllers are the most common form of feedback in control systems (Aström and Murray, 2008). Positioning the body in a handstand is considered as a closed-loop control system (Schmidt and Lee, 2014). An example for this closed-loop control system is stretch reflex in human body which is roughly equivalent to a PID controller in terms of engineering (Hara and Pfeifer, 2003). So, the dynamic behaviour of human press handstand can thus be associated with PID control strategies. The aim of this study was to develop a PID based control model of human press handstand.

**METHODS:** One national gymnast (age 26 years, mass 65 kg, height 1.76 m) participated in this study. The subject performed one successful press handstand with legs together from a piked body position on the floor and maintained the balance position for at least 2 s. Reflective markers were placed on five body landmarks (wrist, shoulder, hip, knee, and ankle joint centers) located at the lateral side (right) of the gymnast. One additional marker was attached to the center of the head. The performance in the sagittal plane was video recorded using a high speed camera (PHOTRON SA3, Japan), operating at a speed of 1000 fps with a shutter speed of 1/2000 s. Prior to data collection, a calibration structure comprising 8 calibration points, was placed in the sagittal view of the movement and video recorded as well. The markers in each video image of the performance and the calibration were automatically digitised using a custom written code in MATLAB (The Mathworks Inc., 2014). Two-dimensional locations of the markers were reconstructed using the 2D Direct Linear Transformation method. Raw marker data were smoothed using a second-order low-pass Butterworth digital filter with a cut-off frequency of 6 Hz. Anthropometric measurements were

obtained in order to get specific body segment inertia parameters within Dempster's (1955) body segment parameters. In order to simulate the performance, a five segment mechanical model of the human body was designed by using SimMechanics (version 4.4) libraries in SIMULINK (version 8.3). Head segment was modelled as a sphere joined to the shoulder with a massless body. The other segments were assumed to be rigid bodies connected to each other by revolute joints. Joint torques were obtained from two-dimensional inverse dynamic analysis by driving the model using joint angle-time histories.

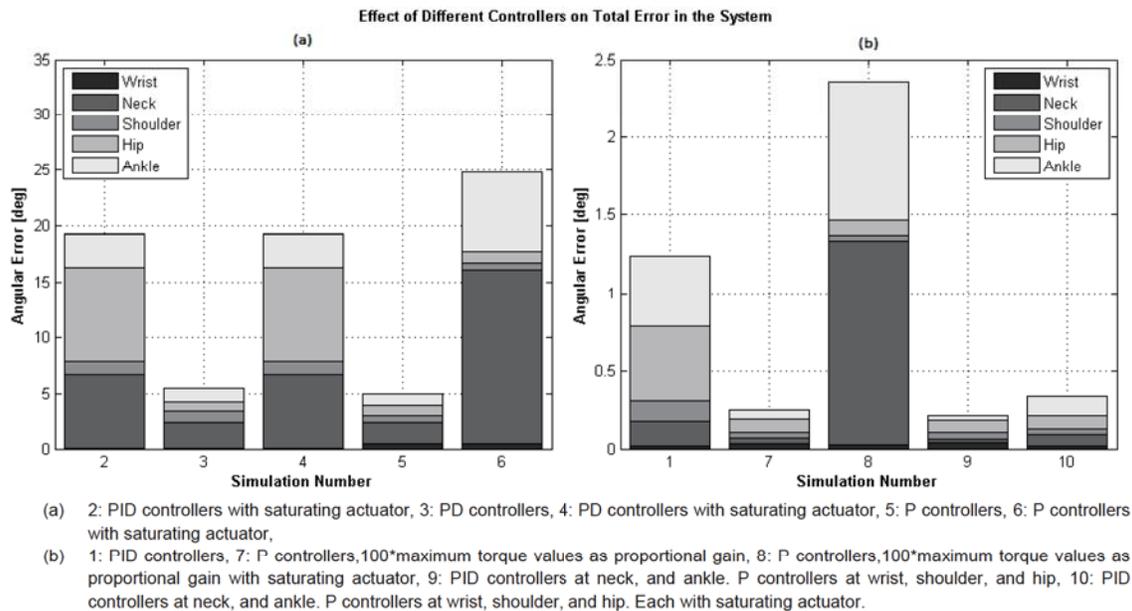
A PID controller was designed for each joint in the simulation model. The input to the model were the actual state of the joints as set points. The gain values of PID controllers were specified by three constants  $K_p$ ,  $K_i$  and  $K_d$  which scale the components of the control torque related to the angular position error signal, the integral of this error signal, and the derivative of this error signal, respectively. First, parameters of the controllers were automatically tuned using PID Tuner of SIMULINK. The torques to be exerted for joint flexion and extension were limited with the maximum and minimum torque values by using saturating actuators. A second auto tuning was performed only for  $K_p$  and  $K_d$  for obtaining a performance close to the actual performance with less parameters, so a PD controller was used at each joint. Then the system was simulated with only proportional control at the joints. A hundred times the maximum torque value of each joint was set as proportional gain ( $K_p$ ) in order to let the controllers respond to the error faster. The error at ankle and neck joints remained, so a last simulation was performed incorporating derivative and integral action into the controllers of ankle and neck joints by adjusting the parameters  $K_d$  and  $K_i$  as well in order to eliminate steady state offsets. All simulations used a variable step size and used the ode15s solver of SIMULINK.

**RESULTS:** The gymnast performed a successful execution of a press handstand and he maintained a proper handstand position for 2 seconds though a bending occurred at trunk. Wrist torques had the greatest magnitude, it is followed by shoulder, hip, and neck while ankle torques had the smallest magnitude through performance. The maximum and minimum torque values of each joint used as upper and lower limits of saturating actuators were presented in the Table 1. The distribution of the integrated control (angular) error values in each simulation was given in Figure 3. Angular error at the joints increased regardless of the controller type when the response of the controllers were limited by using a saturating actuator (Figure 3a-1,3,5 and Figure 3a-8-10).

**Table 1.** The maximum and minimum torque values obtained from inverse dynamic analysis for wrist, shoulder, neck, hip, and ankle joints. The negative wrist torque value was an artifact which can be affected by marker positioning, body segment parameters, simplifications (e.g. trunk as a single rigid body) and accuracy of the model.

Joint	Torque (Nm)	
	Maximum	Minimum
Wrist	105.5	-89.6
Shoulder	49.1	-57.1
Neck	13.3	0.5
Hip	14.6	-19.5
Ankle	2.3	-2.7

The largest angular error was obtained using only a P controller with a saturating actuator where the maximum torque values were set as proportional gain of each joint controller (Figure 3a-6). However using a P controller with maximum torque value as proportional gain for all joints resulted of a lesser error (Figure 3a-7), the steady state error stemming from increased proportional gain caused oscillations at the control signal of neck, and ankle joints. So the smallest error (less than 0.3 degrees at each joint) was achieved when a PID controller was added to neck, and ankle joint (Figure 3a-9). Simulation number 1, 7, 8, 9, and 10 (Figure 3) gave better results where the total system error was less than 2.5 degrees, yet the angular error at ankle, and neck joints had the greatest proportion in the distribution.



**Figure 3.** Distribution of the control error.

**DISCUSSION:** The performer controlled the displacement of mass center by contribution of three joint torques; wrist, shoulder, and hip but the wrist torque had the most dominant role as it was clarified by Kerwin and Trewartha (2001) and Yeadon and Trewartha (2003) before. Since there was a bending at trunk, trunk is considered to be modeled as a multi-link rigid segment in a further study. However the joint angle changes were very small for the neck and ankle joints, the largest error signal was integrated at these joints (Figure 3). Bodies (head and foot) connected to these joints can be recognized as the end effectors of the system since they are the endpoints (Trujano et al. 2011). Obviously, elimination of steady state offsets and anticipation of the future (Aström ve Murray, 2008) were required at the end effectors. However adjusting the parameters of PID controllers automatically gave good results, the magnitude of the control signal exceeded the limits of the actuator saturation block. Therefore reducing the controller parameters and even using only proportional gain was a better strategy. In the study, saturation approach was employed in order to obtain flexion and extension torque values close to the actual performance though it is maybe used for electrical current safety in robotics (Hussain et al. 2014). Concerning the dynamic properties of human body and because of the fact that gymnast might have more muscular force to produce (Prassas et al. 1986), more realistic values for the limits of saturating actuators could be obtained from an isokinetic testing device. Besides, implementing constraints on the joints may be another practical way to avoid unrealistic rotations against

extreme control torques. Further, in our case the reference signal of the controller is not a single setpoint, it changes over time. Instead of adjusting the controller parameters with a given initial condition, the parameters can be updated instantly which would probably improve the performance of the control system (Aström and Murray, 2008). Moreover, a time delay representing conduction, processing, and muscle activation delays (Peterka, 2000), between the actuators and controllers can be implemented to reflect the natural response latency (Schmidt and Lee, 2014) in human motor system.

**CONCLUSION:** This study showed that a P controller can be used with maximum and minimum torque values since proportional gain had the most dominant role in reducing the angular error of all the joints except neck, and ankle. This PID based feedback control model can be improved and used to classify controller parameters of press handstands performed on rings, floor, and parallel bars. Consequently, the results of this study showed that lower level feedback mechanisms such as human stretch reflex operating during a press handstand performance can be represented by various PID based control models.

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