DEVELOPMENT OF A REAL-TIME FEEDBACK CONTROL SYSTEM FOR KNEE JOINT DURING BACK SQUAT

Nihat Şükrü Özgören, Volkan Dağhan Yaylıoğlu and Serdar Arıtan

Biomechanics Research Group, Department of Exercise and Sport Sciences, Faculty of Sport Sciences, Hacettepe University, Ankara, Turkey

The purpose of this study was to develop a proportional-derivative based real-time feedback control system for the knee joint of a back squat performer. This model was used in simulations with four methods and then compared with each other. As a result, a feedback control system was developed which performs real-time control of the knee joint along with inverse dynamics solution during motion. The proposed methods have the potential to be used to control multiple joint actions for various performers using subject specific control parameters.

KEY WORDS: squat, feedback, control, modelling

INTRODUCTION: Motion control is crucial for accuracy and coordination in sports (Schmidt & Lee, 2014) as it is in robotics (Burdet, Franklin, & Milner, 2013) and computer animation (Hodgins, 1998). The neuromuscular control of human movement is provided by various feedback mechanisms (Enoka, 2008; Gautier, Thouvarecq, & Chollet, 2007) which stabilize the body, a dynamic system, throughout the motion. Similar systems are used for feedback control in robotics, mostly different forms of Proportional-Integral-Derivative (PID) controllers (Åström & Murray, 2008). In real-time control, it is necessary to estimate the required torques for a specific motion but numerical solutions introduce errors which may result in failure at realization of motion. In this study, the human body is assumed to be a multi-link machine which uses PD controllers as a feedback mechanism to accurately generate a specific motion. The integral term is excluded since the reference signal is not a single value which makes the feedback from the sum of the past errors useless (Özgören & Arıtan, 2016). From this point of view, the purpose of the current study is to develop a real-time control of human motion in sports, particularly knee joint during back squat, using an improved PD control method.

METHODS: One male athlete (age 28 years, 65 kg, 1.76 m) participated in this study. The participant performed seven repetitions of back squat with 75% of his predetermined 1 repetition maximum (75 kg) which was calculated via the description of Kraemer and Fry (1995). Four reflective markers were attached to selected body landmarks (ankle, knee, and hip joint centres, and toe) on the right side of the athlete. One additional marker was placed on the mid torso in order to estimate the location of shoulder joint. Seven repetitions of the performance in the sagittal plane was video recorded using a high speed camera (PHOTRON SA3, Japan), operating at a speed of 125 fps with a shutter speed of 1/500 s. A calibration structure comprising eight calibration points was placed in the sagittal view of the motion and recorded prior to data collection. Markers in the recorded video images were automatically digitized by using a custom written code in *MATLAB* (version R2017b). 2-D world coordinates of the markers were then calculated using 2-D Direct Linear Transformation method. In order to eliminate the fluctuations, the raw coordinate data were filtered using a second-order low-pass Butterworth digital filter with a cut-off frequency of 8 Hz. Anthropometric measurements were performed and individual specific body segment inertia parameters were calculated by using body segment parameters of Dempster (1955) for future use in simulation model.

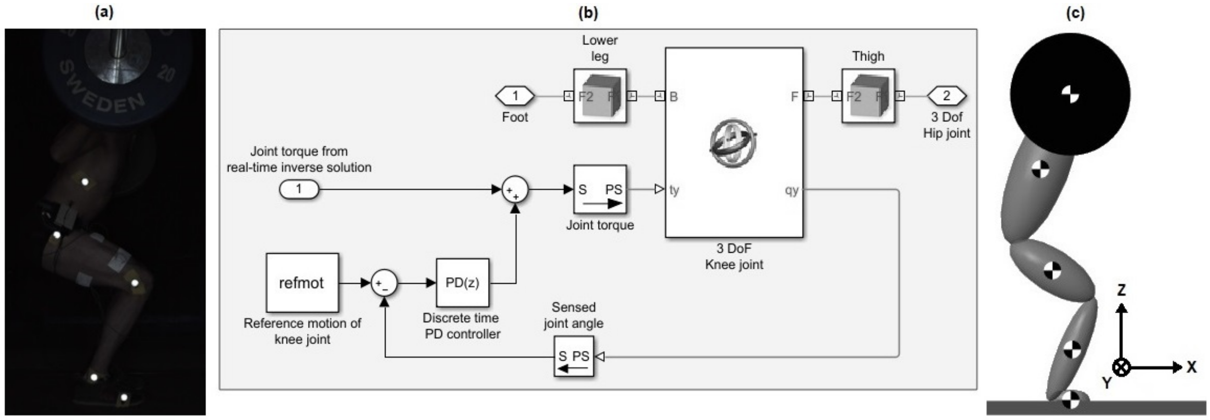

Figure 1. (a) A frame from the captured back squat performance of the participant, (b) block diagram of designed mechanical model of knee joint in *Simulink,* (c) the simulation model.

A four-segment mechanical model of the athlete comprising foot, lower leg, thigh, and torso was built (Figure 1c) by using SimMechanics libraries (version 5.1) in *Simulink* (version 9.0). All the segments were assumed to be rigid ellipsoids connected to each other by revolute joints. The weight (including barbell) was modelled as a rigid cylinder with a radius of 0.22 m and connected to the shoulder joint using a weld joint. The mass of arms and head was added to the mass of the weight for a more realistic representation. Inputs to the model were joint angle – time histories, joint initial positions, segment angle – time history of the foot and segmental inertia parameters.

Five simulations were performed using the ode4 (Runge-Kutta) solver of the *Simulink* with a fixed step size, 0.008 s in the following order;

1. Joint torques and ground reaction forces were obtained from 2-D inverse dynamic analysis.
2. Rotation at the knee joint was controlled by a PD controller (Figure 1b) in the discrete time domain. The gain values of the controller were specified by two constants, K_p and K_d which outputs the control torque depending on the amount of angular error and derivative of this error respectively. The gains of the controller were automatically tuned by using PID Tuner of *Simulink.*
3. Gravitational torques acting about the knee joint were calculated in real-time for each time step and used for joint actuation together with the control torques of the controller.
4. Required torques to generate the knee motion were calculated in real-time for offsetting forward PD controller output.

RESULTS: All methods gave closely matched results (Figure 2a) yet there were minor differences (Figure 2b). The auto-tune algorithm gave the same parameters for all methods except PD controlled motion with gravity offset especially for the proportional gain (Tables 1 and 2).

Table 1. Errors for different methods with respect to the reference motion.

	PD controlled motion	PD controlled motion with gravity offset	PD controlled motion with reference torques	PD controlled motion with real-time inverse solution
Mean absolute deviation (degree)	0.0540	0.0784	0.0094	0.0398
Maximum absolute error (degree)	0.2116	0.1871	0.0654	0.2073

Table 2. The parameters of the PD controller used in all methods.

	PD controlled motion	PD controlled motion with gravity offset	PD controlled motion with reference torques	PD controlled motion with real-time inverse solution
K_p	73515.25	114265.28	73515.25	73515.25
K_d	6281.37	6827.57	6281.37	6281.37
N	194.16	243.31	194.16	194.16

K_p: Proportional gain, K_d: Derivative gain, N: Filter coefficient

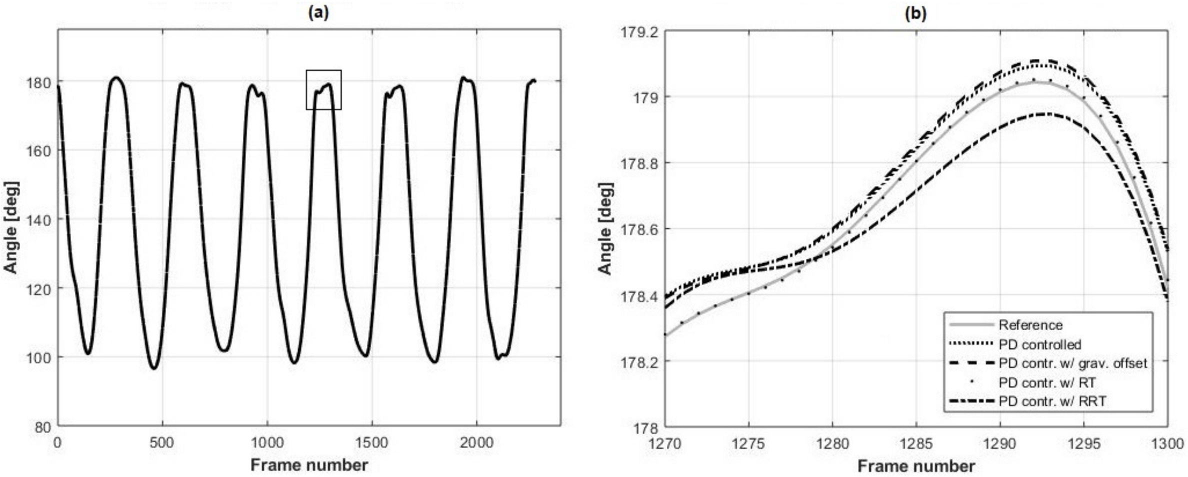

Figure 2. Knee joint angles for different methods (a). When zoomed in (b) subtle differences are more pronounced.

Both graphs use grey line for reference motion, dotted line for PD controlled motion, dashed line for PD controlled motion with gravity offset, scarce-dotted line for PD controlled motion with reference torques, dash-dotted line for PD controlled motion with real-time inverse dynamics solution.

DISCUSSION: Each method gave arguably satisfactory results in tracking the reference motion. The best results were obtained via pre-calculated inverse dynamics solution yet it didn't facilitate real-time motion control. In order to obtain a better performance than that of PD control, we used two approaches and compared their results with the precomputed inverse dynamics solution. First, actuating the knee joint with the reference torques by lagging inverse dynamics simulation of the model with same parameters. Second, noting that pre-calculated inverse dynamics solution is sufficient for satisfactory results, we searched for the necessary parts of pre-calculated inverse dynamics solution for similarly satisfactory results. From this point of view, gravitational torques acting about knee joint were calculated in real-time and these torques were used to offset the control torques exerted by PD controller. Since our method tries to match the necessary torques using errors in motion, this method is supposed to reduce the burden of PD controller by removing highly nonlinear effect of gravitational forces. Therefore, the solver could focus on merely dealing with the rest of the motion. This effect could be seen at Table 2 where the linear coefficient (K_p) increases whereas the differential coefficient (K_d) decreases. One step further would be to include nonlinearity resulting from moment arm to this method.

In a previous study (Özgören & Arıtan, 2016) various PID tuning methods were tested for controlling a single motion for a multi-joint model and this study builds upon that by using multiple motions with an improved PD control method. Since we aim to find unique PD parameters which will work for similar motions of the same person, we tuned the parameters of the controller for a single repetition and assessed its performance for multiple repetitions. It should be noted that the parameters of the controller were tuned automatically using PID Tuner of *Simulink* which raises the question if there is a better approach, maybe a custom tuning algorithm. We improved our previous method (Özgören & Arıtan, 2016) by using discrete-time implementation of backward Euler method in fixed steps instead of continuous time implementation of forward Euler method in variable steps. Moreover, the control torques exerted by the controller for knee extension were found to be similar to those obtained from inverse dynamics analysis thus a saturation was not employed.

As in many motions, back squat includes a closed-loop control at low level. PD controller at knee joint provides a low level control via feedback like a stretch reflex (Reil & Massey, 2003). In reality, there are several muscles around a particular joint. In this study, it was assumed that all the muscles around knee joint act in an integrated manner so we used PD controller as a joint actuator which reduced the degrees of freedom of the system. This study is considered as a step towards our main goal: representing the control strategy of human motion in terms of robotics and finding subject specific controller parameters (K_p and K_d). Finding such a quantifier for motion control may lead to a key for improved athletic performance.

CONCLUSION: Although PD controller provides a numerically consistent simulation supplementing raw inverse dynamics solution by itself, it was improved by proposed methods for real-time control of human motion. These methods might lead us to control multiple joints instead of a single joint in dynamic motions. Nevertheless, they are to be tested for squats with different weights and with different performers which would provide various motion patterns.

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