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QUANTITATIVE EVALATION OF DEXTERITY BY MODELING OF JOINT TORQUE

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The aim of this study is to quantitatively evaluate the stretch reflex on athletic motions. In this study, we regard stretch reflex as an index of dexterity because dexterous motions effectively utilize the stretch reflex by relaxing the stiffness of articulations. Subjects were one skilled and one unskilled. They performed power clean that is a typical strength training motion. We measured trajectories of joints by using the motion capture system, numerically filtered, differentiated, and calculated the articulation torques. In order to evaluate the strength of stretch reflex, we employ a time series curve fitting method in the proposed torque model that includes a term caused by stretch reflex. The results indicate that the skilleds' strength of stretch reflex shows large value, compared to the unskilled's one. This suggests that the proposed torque model and the analytic method allow us to quantitatively measure dexterity.

KEY WORDS: stretch reflex, torque model, recursive least squares method.

INTRODUCTION: The aim of this study is to quantitatively evaluate the stretch reflex on athletic motion. In some sports actions highly skilled athletes hold their articulations in respectively low stiffness state, the purpose of which will be twofold. One is to comply and absorb contingent external disturbances, and two is that the low-stiffness allows them to effectively utilize the reaction stemming from stretch reflex against external force or torque. Here we will use the term "stiffness" to refer to the rigidity of joints and is typically measured in the unit [Nm/rad]. The complementary concept is "flexibility" or "compliance". It sometimes requires them a long and hard training to acquire the capability to dynamically adjust the stiffness according to the change of external interferences. It is obvious that some disciplined actions do not rely on any neurological feedback passing through cerebral cortex or cerebellum because of demanding acuteness of the responce. Let us now look at them in detal. Making articulations relax, which rephrases to gain the low-stiffness state, allows the athletes not only to passively adapt abrupt changes of external force or torque, but also to react or regulate it by the response due to the stretch reflex after short latency time due to proprioceptive feedbacks on the spinal code level (Akazawa et al. 1983). Bernstein duly defines the *dexterity* as the ability in the above mentioned context (see Latsh,et.al.. 1996). Therefore quantitative measuring of the stretch reflex will contribute to assess how much the athletes acquire a dexterous behavior.

Here, we propose a new torque model of articulations during a sports exercise that includes a term with respect to stretch reftex. Moreover, we employ the recursive least square method (RLSM, hereafter) to calculate the time courses of the coefficients multiplied in each terms in the torque model. Finally we evaluate the results, especially the diffferences between the skilled and the unskilled subjects and totally discuss the obtained results in the view point of dexterity.

METHODS: We take the power clean motion (PC, hereafter) for weight-lifting training (Hori et al. 2005). The PC is a typical exercise that is appropriate for evaluating the dexterity due to the following reasons; (1) It is a typical synergic motion, in which hip, knee and ankle joints simultaneously coactivate, which can be seen in many athretic motions. (2) We can quantitatively identify the difference between the skilled and the unskilled. (3) Athletes are required to lift up the heavy barbell (more than their body weight) in a short period of time, which does not have a room to control by the level of a central nervous system. (4) Athletes are also required to cope with a contingent deviation of the barbell's trajectory.

The subjects are two male college students. They were selected as one skilled and one unskilled based on typical criteria as "PC 100% one repetition maximum/body weight" exceeding 1 or not. The subjects' data are as follows; the skilled (age: 20yaers, height: 172.3cm, body weight: 76.3kg, PC 100% one repetition maximum: 102.5kg) and the unskilled (age: 21yaers, height: 172.0cm, body weight: 73.0kg, PC 100% one repetition maximum: 60.0kg). They performed PC of which intensity is set at 70%. Analytical range of PC motion is from the start of lifting the barbell to the standstill state. The position trajectories of markers attached on the subjects' bodies during PC are recorded by the 8-camera motion capture system with sampling freq. 250Hz (Cortex3, Motion Analysis). Motion capture data were low-pass filtered using a zero-lag 4th order Butterworth filter with cut-off 6Hz.

A link segment model in sagittal plane was used to calculate lower limb joint torque. The segment mass and moment of inertia were derived on the basis of the body segment inertia parameter (Ae et al. 1992). The angle, angular velocity and angular acceleration of each joint are calculated from motion capture data. The joint torque τ_i of hip, knee and ankle are calculated according to the dynamic equations given by the Lagrange's formulation. COP is also calculated from the obtained kinematics data (Takahashi et al. 1985).

We establish the following torque model;

$$\tau_i(t) = \tau_{fi} + \alpha_{zi}\,\bar{p}_{wz}(t-\Delta t_w) + \alpha_{xi}\,\bar{p}_{cop}(t-\Delta t_w) - \gamma_i\, sig(a, \dot{\theta}(t-\Delta t_\gamma)) + \tau_{ei}(t) \tag{1}$$

In Eq.(1), α_{zi} (> 0) and α_{xi} (> 0) are coefficients that represent the strength of sensory feedbacks with respect to the vertical position of the barbell and the horizontal position of the COP respectively, and γ_i (> 0) is the one representing the strength of stretch reflex on each joints. The parameters are calculated by the method described below. The fourth term including γ_i is designed to involve the lag-time Δt_γ inherent of stretch reflex. *Sig* is a sigmoid function that specifies the effect of the stretch reflex as a function of joint angular velocity.

$\bar{p}_j(j = wz, cop)$ is calculated by,

$$\bar{p}_j(t-\Delta t_w) = \left(\frac{\partial p_j(t-\Delta t_w)}{\partial \theta_i}\right)^{-1}\left(p_{fj} - p_j(t-\Delta t_w) - 2\zeta\frac{1}{\omega_n}\dot{p}_j(t-\Delta t_w) - \frac{1}{\omega_n{}^2}\ddot{p}_j(t-\Delta t_w)\right) \tag{2}$$

where p_{fwz} and p_{fcop} represent the desired barbell vertical position and the desired COP position at the standstill, respectively. The formulation of Eq. (2) allows the feedbacks on a second order dynamic approaching with a natural angular frequency ω_n and a damping coefficient ζ . It may be interpreted that $\bar{p}_{wz}$ represents an active control torque to execute the PC in a conscious level, while $\bar{p}_{cop}$ is one for stabilizing a posture during PC in a spinal code level as well as a stretch reflex torque (the fourth term in Eq.(1)). τ_{fi} is the joint torque that is required to keep final posture, In equation (1), the last term τ_{ei} is the viscoelasticity resistance torque of the joint, which is calculated by Aoki & Yamazaki (1998) method using angle and angular velocity of each joint.

In order to calculate α_{zi}, α_{xi} and γ_i , we perform curve fitting with RLSM using the calculated joint torque

$$\begin{bmatrix} \alpha_{zi}(t_n) \\ \alpha_{xi}(t_n) \\ -\gamma_i(t_n) \end{bmatrix} = \left(\boldsymbol{I} - \omega_n\ \boldsymbol{\xi}_n\ \boldsymbol{\lambda}_n^{\mathrm{T}}\right)\begin{bmatrix} \alpha_{zi}(t_{n-1}) \\ \alpha_{xi}(t_{n-1}) \\ -\gamma_i(t_{n-1}) \end{bmatrix} + \boldsymbol{\Sigma}_n^{-1}\boldsymbol{u}_n \tag{3}$$

Eq.(3) is the RLSM equation, where *n* is the data number. RLSM is the method that calculates *n*th results using the previously calculated (*n*-1)th results. Setting initial values as,

$$\boldsymbol{\Sigma}_0^{-1} = \mathrm{diag}\left[\ g\quad g\quad g\ \right] \qquad \left[\ \alpha_{zi}(t_0)\quad \alpha_{xi}(t_0)\quad -\gamma_i(t_0)\ \right]^{\mathrm{T}} = \left[\ 0\quad 0\quad 0\ \right]^{\mathrm{T}}$$

with a large value of g, then variables appeared in the Eq.(3) are calculated by the following order.

$$\boldsymbol{\lambda}_n = \left[\ \bar{p}_{wz}(t_n - \Delta t_w)\ \ \bar{p}_{cop}(t_n - \Delta t_w)\ \ \dot{\theta}_i(t_n - \Delta t_\gamma)\ \right]^{\mathrm{T}} \qquad \boldsymbol{u}_n = (\tau_i(t_n) - \tau_{fi} + \tau_{ei}(t_n))\,\boldsymbol{\lambda}_n \boldsymbol{\xi}_n \quad ; \tag{4}$$

$$\boldsymbol{\xi}_n = \boldsymbol{\Sigma}_{n-1}^{-1}\boldsymbol{\lambda}_n \qquad \omega_n = \frac{1}{\rho + \boldsymbol{\lambda}_n^{\mathrm{T}}\boldsymbol{\xi}_n}; \qquad \boldsymbol{\Sigma}_n^{-1} = \frac{1}{\rho}\left[\ \boldsymbol{\Sigma}_{n-1}^{-1} - \omega_n\, \boldsymbol{\xi}_n\, \boldsymbol{\xi}_n^{\mathrm{T}}\ \right] \quad ;$$

where ρ (< 1) is a forgetting factor that determines the influence of the past data. RLSM allows calculating the dynamic change of coefficients as time variables. Athletic motions and their nerve control on the spinal cord level are varied in short time. So we consider the RLSM having high relevance to be used for analysing them rather than normal Least squares method. Moreover, the advantage of RLSM is in its very short calculation time, because there is no need to calculate inversion of covariance matrix ($\boldsymbol{\Sigma}_n^{-1}$ Eq.(4); it is also calculated by using one-step ahead result $\boldsymbol{\Sigma}_{n-1}^{-1}$). This fact allows us large scale computation.

RESULTS & DISCUSSION: Figure 1 shows knee angle during PC motion of skilled and unskilled, respectively. It is observed that the knee flexion-extension occurs in the skilleds' motion, which suggests that the skilled has acquired "double knee bent (DKB, hereafter)" that is unique technique in skilled weight lifters (Chiu et al. 2005). On the other hand, in the case of the unskilled, the DKB did not emerge. This fact clearly suggests the selection of skilled and unskilled subjects in our study was valid.

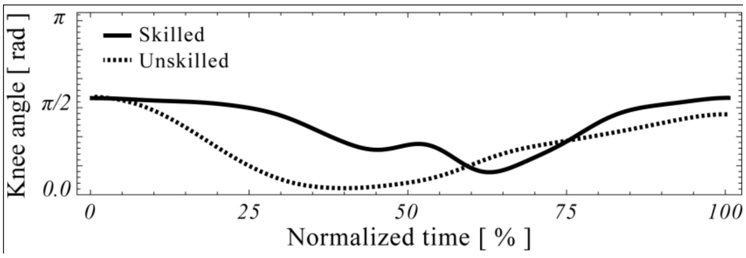

Figure 1: Time courses of knee angle during PC

Figure 2 shows the results of lower limbs joint torque during PC motion, which was calculated from the derived dynamic equations.

Figure 3 shows the curve fitting results of skilled and unskilled during PC motion by using the torque model in Eqs. (1)(2). We set the value of arbitrarily-determined constants in Eqs. (1)(2) so that they led the best fit of the torque. Their selection ranges are as follows by considering the physical conditions;

Δt_γ = 20~50 ms, Δt_w = 10~30 ms, ω_n = π/4~2π rad/s, ζ = 0.1~1.0, ρ = 0.95~0.99 and g = 1000.

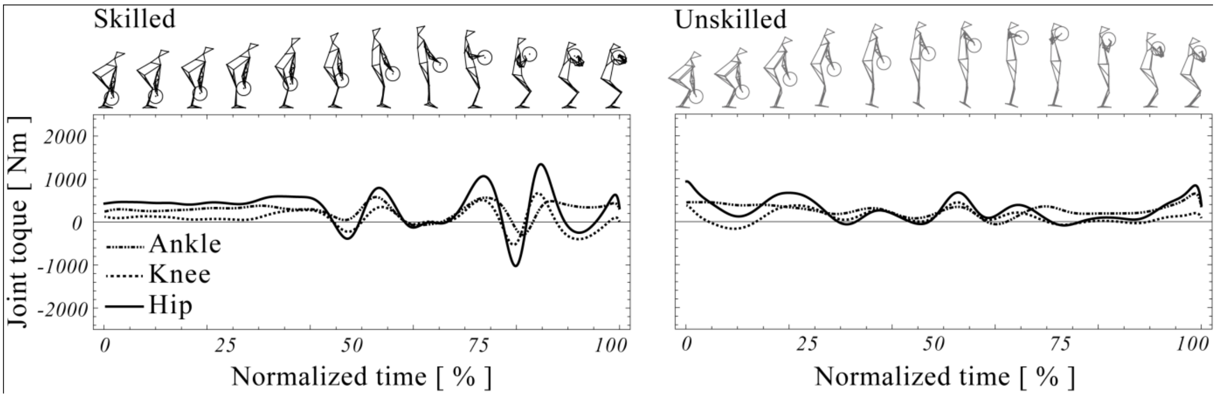

Figure 2: Time courses of joint torque during PC

In Fig.(3) it is observed that the good curve fittings are obtained in the case of the hip and the ankle data both of skilled and unskilled. Whereas the knee data on both skilled and unskilled are not so good. On a wide range of period, skilleds' γ shows larger value than the unskilleds'. Especially, at the moment of almost 40% in normalized time, the γ of the knee is increased rapidly, which suggests the knee joint is under a low-stiffness state during DKB motion. Moreover, it is possibly to say that the γ increase means the stretch-shortening cycle behavior of knee extensor muscles. Because the knee extensor muscles are extended with knee flexion. Skilleds' hip α_z shows larger value than any other joint's α_z, which indicates that skilled lifted the barbell by hip joint torque mainly. Enoka (1988) reported that there are significant correlation between maximum hip joint torque and the best record in weight lifting competition, so hip joint toque has primary role for lifting. Our results agree with that study. Skilleds' γ and α_x of ankle shows large value than those of unskilled, which refers to that skilleds' ankle is under low-stiffness state to enhance the stretch reflex. Thereby, skilled adjusts COP position to obtain whole body stability.
From the above, it seems that the obtained dynamic change of γ value accurately reflects the rational strategy of skilled's PC motion, which enables us to assess the dexterity of the motion.

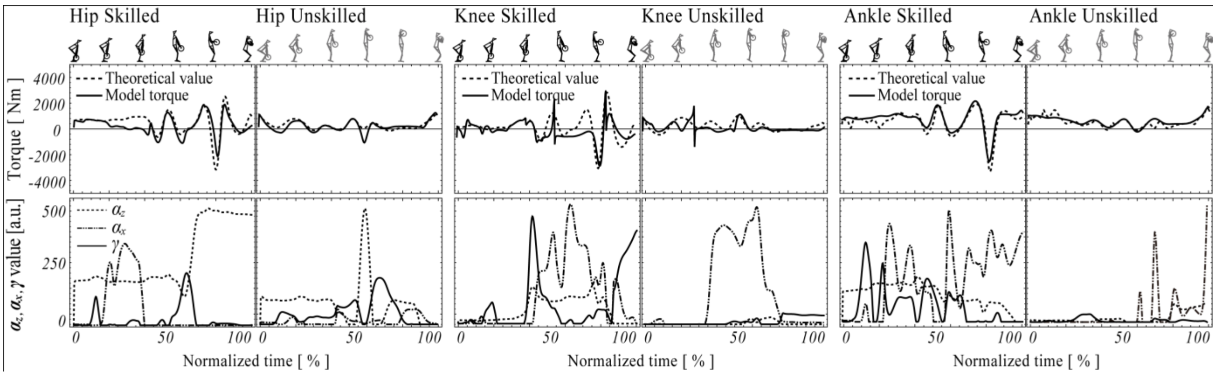

Figure 3: Curve fitting and the parameters value of hip, knee and ankle joint

CONCLUSION: In this paper, we present a method to quantitatively evaluate stretch reflex in athletic motion. Using the method we analysed PC motion as a typical athletic motion. Our torque model includes a feedback term caused by stretch reftex and a proprioceptive feedback term caused by COP. We employ the RLSM to calculate the time courses of the coefficients of them. The advantage of the proposed methods is able to calculate time-variant parameters continuously. It was found through experiments that each coefficient values, which calculated by torque model, accurately reflects the reality of motion, especially the skilleds' stretch reflex coefficient γ shows larger value than unskilled over a wide range of result.
From these experimental results, it can be confirmed that the proposed method paves the way to quantitatively evaluate the dexterity in dynamic motion. The presented methodology can be applied in any other athletic exercises although torque model should be altered in accordance to the motion.

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