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Original Article

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Torque, Work, Power, and Muscle Activity Analysis According to Self-Selected Slow, Moderate, and Fast Angular Velocity for Knee Extension

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Purpose: The performance of a task is influenced by the perception of its demands and the development of a response according to the movement pattern. This study aims to compare the change in kinetic variables and quadriceps muscle activity according to demands on angular velocity.

Methods: Thirty-eight participants performed knee extensions at self-selective angular velocities of slow, moderate, and fast. Angular velocity, kinetic variables, and muscle activity (vastus medialis, vastus lateralis, and rectus femoris) were measured using a dynamometer and surface electromyography. kinetic variables and muscle activity of the knee extensors at three self-selected angular velocities were compared and correlations between the variables were analyzed.

Results: There were significant differences in muscle activity and kinetic variables among angular velocities ($p<0.001$). Self-selective angular velocity was positively correlated with muscle activities and kinetic variables ($p<0.001$). The power in fast was 40 times higher than that in slow velocity.

Conclusion: The simultaneous increase in angular velocity and force output was based on increased effort. The highest power was indicated for the fastest movement. We discovered that muscle activity and torque increased at a similar rate for increasing demands on angular velocity. The individual's most appropriate pattern would have been applied at the movement of self-selective angular velocity, and fast movement is considered to have the highest efficiency.

Keywords: Biomechanics, Knee extensors, Movement angular velocity, Self-selective angular velocity, Muscle activity

INTRODUCTION

The definition of "muscular strength" is the ability to exert force on an external object or resistance. Higher levels of muscular strength can increase functional performance and reduce the risk of injury.[1] Resistance training is commonly used to improve muscular strength. The intensity of the resistance training program can be modified using the following variables: resistance, angular velocity of movement, distance moved, exercise selection and order, number of sets and repetitions, frequency, and resting period.[2] In order to the scientific design of resistance training, changes in biomechanical data including muscle activity should be determined in response to systematically increasing the demands placed on the body. Considering the most used isotonic exercise as an example, an increase in load results in an increase in the exercise demand for the subject.[3]

Isotonic exercise, widely recognized as a predominant strength training technique, encounters a limitation where the maximal resistance is confined to the load at the weakest point across the full range of motion.[3] Conversely, isokinetic exercise, by setting a constant maximum velocity, theoretically enables maximal force generation throughout the entire active range of motion.[4] Previous studies comparing isokinetic variables

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(torque, power, work, etc.) according to angular velocity used constant angular velocity for fast (e.g., 200-300°/s) and slow (e.g., 60-120°/s) velocities.[5-11] Another study reported a linear model of the force-velocity relationship in which an increase in velocity was accompanied by a decrease in muscular strength.[12] In isokinetic exercise, angular velocity is inversely proportional to torque and work values, while it is proportional to power.[13] However, muscle force/torque control was influenced by task, sex, age, etc.[13,14] A study of the relationship between force and electromyography (EMG) for knee extension discovered that it can be used as a rough estimate of force, despite slight deviations in the linearity of the quadriceps EMG.[15] However, there have been inconsistent reports of an increase, a decrease and no change in EMG amplitude with increasing angular velocity.[3,5,6,9,11,16] In isokinetic exercise, the participant is required to exert their best effort in an entire range of motion (ROM) while the selected maximum angular velocity is limited by the exoskeletal device.[4] Because participants require maximum effort for both angular velocities, it can be considered that there are similar performance demands. However, for the generally applied isokinetic exercise, the question regarding the exercise demand for the subject remains. The way an individual responds to performing a given task is influenced by the perception of the task's demands and the scope of this response runs along a continuum.[17]

Therefore, to determine the effect of angular velocity, an investigation of the effect of different demands on velocity rather than specifically constrained velocity is necessary. This study aims to compare the change in the kinetic variables (peak torque, PT; average torque, AT; total work, TW; peak power, PP; and average power, AP), and quadriceps concentric muscle activity (EMG activity) according to changes in the demand for movement angular velocity and the correlation between velocity and acquired data.

Our research hypotheses are as follows: 1) the performance of a task would be influenced by the perception of its demands and the development of a response according to the movement pattern. 2) As angular velocity increases, the demands of performing a task will increase. 3) As angular velocity increases, the kinetic variables will increase. 4) As angular velocity increases, muscle activity will increase.

METHODS

1. Subjects

In this cross-sectional study, healthy young adults were recruited through printed and electronic advertisements on notice boards in the university from June 2021 to December 2021. Subjects who were physically active and not currently involved in another exercise program participated in this study. Participants had no previous lower limb injury, neurologic disorder, or cardiovascular disease. In addition, people who were deemed unsuitable for participation by the researcher were unable to participate. A total of 38 healthy young adults (19 men, 19 women, age = 23.2 ± 2.1 years, height = 166.8 ± 8.6cm, body mass = 63.0 ± 13.8kg, body mass index = 22.4 ± 3.4kg/m^2) volunteered to participate in this study. Data from all enrolled participants were used for analysis.

This study has been approved by the Institutional Review Board of the authors' affiliated institutions. Additionally, this study was conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all participants.

2. Experimental procedures

1) Measurement

(1) Knee extensor muscle function at the self-selective angular velocity

An isokinetic dynamometer (HUMAC NORM, CSMI Medical Solutions, Stoughton, USA) was used to assess knee extensor muscle function (kinetic variables) at self-selected slow, moderate, and fast angular velocities (Figure 1). Analog output data were converted to digital in the same data acquisi-

Figure 1. Isokinetic dynamometer

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tion system of the dynamometer and recorded in synchronization with the EMG data. Kinetic variables data collected from the dynamometer were sampled at 1,000Hz and smoothed using a rolling average calculated every 50 samples.

Before obtaining the measurements, participants performed a 5-minute warm-up at their own pace using a cycle ergometer (NB 7.0r Recumbent Bike, New Balance fitness, Ohio, USA). Subsequently, 3-minute after the warm-up, participants were instructed to sit in a dynamometer chair with a hip flexion of 85°. The axis of the dynamometer was aligned with the lateral epicondyle of the knee, and the force pad was placed approximately 3cm above the medial malleolus. The trunk and the thighs were secured using straps. The dominant leg was measured, which was identified as the leg usually used to kick the ball.[12] Before performing knee extension, participants were asked to determine and move at three subjectively perceived (self-selective) angular velocities: slow, moderate, and fast. Participants performed concentric knee extension at three self-selected angular velocities using the isotonic mode of the dynamometer. In isotonic mode, the resistance value was set to zero (no load). In other words, according to these settings, participants were able to freely perform knee extension except for the force pad weight of the dynamometer. The knee joint's ROM was set from 90° flexion to maximal voluntary knee extension (0°). The order of the knee extension tests at three self-selective angular velocities was assigned randomly to each participant and separated by a 5-minute rest interval to minimize muscle fatigue. Three trials were performed at each angular velocity, and a 30s rest was allowed between each trial.

Three self-selected angular velocity values (in degrees per second) were extracted from raw data obtained during isotonic contractions. This was calculated as the average of the recorded angular velocities within the ROM while performing knee extension. To evaluate knee extensor function, we determined the kinetic variables (PT, AT, TW, PP, and AP). All kinetic variables were expressed as the mean values of three trials. PT, TW, PP, and AP were obtained through the dynamometer's report. We calculated AT directly from extracted raw data. PT (Newton meters; N·m) and AT (N·m) refer to the maximum and mean torque values, respectively, and TW (joule, J) represents the total work performed by the knee joint.[18] To compensate for individual differences related to body mass, the measured values were normalized for each.[3]

(2) Electromyography

The EMG measurements were conducted using the wireless surface EMG system (Zero Wire EMG, Aurion, Oderzo, Italy)(Figure 2). Muscle activity data were exported to the A/D converter of the EMG recording system and then collected and analyzed using MyoRESEARCH software (XP Master, version 1.07.1, Noraxon, Arizona, USA) installed on a personal computer. EMG data were acquired for the vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF) muscles during knee extension with three self-selective angular velocities. Because agonist muscles have a primary role in generating force in the directions prescribed, the activity of these muscles was included in the measurements.[19] Skin preparation, such as shaving the electrode sites and cleaning the skin with rubbing alcohol, followed the Surface EMG for the Non-invasive Assessment of Muscles guidelines while attachment placement of the Ag-AgCl electrode was determined according to the previous study.[3,20]

To normalize EMG data, participants completed a maximal voluntary isometric contraction (MVIC) test of the knee extensors using the isometric mode of an isokinetic dynamometer. In the MVIC test, the knee and

Figure 2. Wireless surface electromyography system

hip joints of the examined limb (dominant limb) were maintained in 60° and 90° flexion, respectively.[21,22] Three 5-second trials were recorded with 2 minutes of rest in between. The first and last seconds were discarded, and the RMS value for the 3 seconds present in the middle was calculated. The highest value of the three MVIC consecutive tests was used for analysis.[23] EMG signals obtained during the knee extension were normalized to the MVIC (%MVIC). All raw EMG signals acquired during knee extension and MVIC tests were sampled at 1,000Hz and were band pass-filtered between 20 and 450Hz. The filtered signals were full wave rectified and smoothed using the root mean square (RMS) with a 100ms window.

3. Statistical analysis

The Shapiro-Wilk test was used for the normality test of all data. Normality was not assumed for the variables collected in this study, which led to the use of nonparametric statistics. Kruskal–Wallis one-way analysis of variance (two-tailed, significance level $\alpha = 0.05$) was applied to compare the kinetic variables and muscle activity of the knee extensors at three self-selective angular velocities. A Mann-Whitney U test was used for post hoc analysis, and Bonferroni correction (0.05/3) was applied (two-tailed, significance level $\alpha = 0.0167$). Spearman rank-order correlation test was used to analyze the correlation of the self-selective slow, moderate, and fast angular velocities with kinetic variables and muscle activity (0.0-0.1: no correlation, 0.1-0.4: weak correlation, 0.4-0.6: moderate correlation, 0.6-0.8: strong correlation, >0.8: very strong correlation).[24] All data were analyzed using IBM SPSS (IBM Corp., Armonk, NY, USA). $p < 0.05$ was considered statistically significant and effect sizes (ES) were calculated using Cohen's d.

RESULTS

Table 1 depicts the differences in the kinetic variables (PT, AT, TW, PP, and AP) and muscle activity (VM, VL, and RF) of the knee extensors during concentric contraction according to the three self-selective angular velocities. The self-selective slow, moderate, and fast angular velocities (°/s) of the knee extension were measured to be 27.82 ± 18.65 (range: 29.48-48.26), 80.06 ± 19.66 (43.57-142.32), and 122.6 ± 23.31 (76.66-192.15), respectively. The relative ratios of moderate and fast angular velocities to slow velocity were 287.78% and 440.69%, respectively. Also, the relative ratio of fast to moderate angular velocity was 153.14%. Significant differences were observed in the kinetic variables among the angular velocities ($p < 0.001$). According to the results of the Mann–Whitney post hoc tests, PT, AT, TW, PP, and AP values at fast angular velocity were significantly greater than those at other velocities ($p < 0.001$). These values were also significantly higher at moderate than at slow velocity ($p < 0.001$). Additionally, significant differences were observed in muscle activity according to angular velocity. The result of the post hoc tests revealed that VM, VL, and RF muscle activity at fast angular velocity were significantly higher than at other velocities ($p < 0.001$). Muscle activity at moderate angular velocity was significantly greater than at slow velocity (VM; $p < 0.001$, VL; $p < 0.01$, RF; $p < 0.05$).

Figure 3 presents the correlation between the self-selective angular velocity of knee extension and kinetic variables. The angular velocity has a very strong positive correlation with PT, TW, AP, and PP ($p < 0.001$), and a strong positive correlation with AT ($p < 0.001$). Figure 4 illustrates the correlation between angular velocity and muscle activity in knee extensors.

Table 1. Comparison between kinetic variables and muscle activity of knee extensors according to self-selective angular velocities (N = 38)

Variable	Slow	Moderate	Fast	df	Chi-square	p-value[a]
Self-selective angular velocity (°/s)	27.82 (18.65)	80.06 (19.66)	122.60 (23.31)			
% Slow velocity[b]	100	287.78	440.69			
Kinetic variables						
Peak torque (Nm/kg)	0.08 (0.03)	0.24 (0.10)	0.62 (0.26)	2	90.432	<0.001*,**,†
Average torque (Nm/kg)	0.04 (0.04)	0.09 (0.07)	0.19 (0.10)	2	54.704	<0.001*,**,†
Total work (J/kg)	0.04 (0.03)	0.17 (0.09)	0.55 (0.29)	2	88.736	<0.001*,**,†
Peak power (W)	3.18 (3.65)	25.16 (18.29)	130.76 (90.80)	2	89.845	<0.001*,**,†
Average power (W)	1.24 (2.16)	11.66 (8.32)	60.37 (42.48)	2	89.816	<0.001*,**,†
Muscle activity (% MVIC)						
Vastus medialis	13.95 (7.70)	22.63 (13.49)	67.06 (38.21)	2	45.684	<0.001*,**,†
Vastus lateralis	16.77 (7.94)	24.89 (16.37)	68.01 (43.29)	2	45.684	<0.001*,**,†
Rectus femoris	19.06 (9.66)	25.18 (11.44)	57.68 (25.61)	2	38.105	<0.001*,**,†

Data are presented as mean (standard deviation). df: degrees of freedom, MVIC: maximal voluntary isometric contraction. [a]Post hoc test; Mann-Whitney U test, [b]The relative ratios of self-selective moderate and fast angular velocities to slow velocity in knee extension. *slow < moderate, **slow < fast, †moderate < fast.

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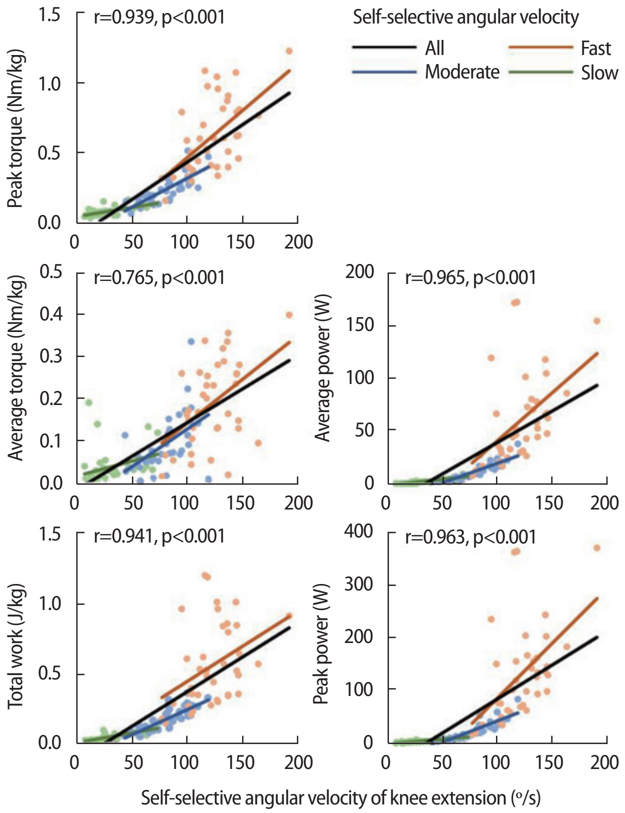

Figure 3. Correlation between self-selective angular velocity of knee extension and kinetic variables

The angular velocity has a strong positive correlation with each muscle activity corresponding to VMO, VL, and RF ($p < 0.001$).

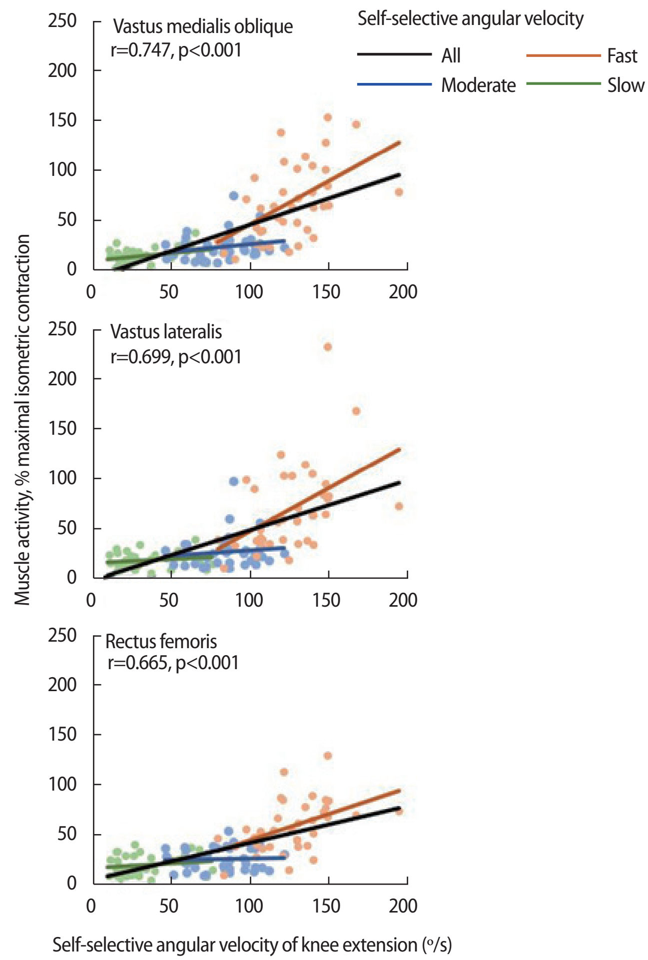

Figure 4. Correlation between self-selective angular velocity of knee extension and muscle activity

DISCUSSION

This study investigated the changes in kinetic variables and muscle activity of the quadriceps according to the increase in demand for movement angular velocity. The angular velocities of the self-selective fast and moderate were 122.6°/s, and 80.06°/s, respectively, which was 4.4 times and 2.9 times quicker than that of the slow velocity (27.82°/s).

In previous studies, the increase or decrease in muscle activity with an increase in angular velocity was debated.[3,5,6,9,11,16] Tillin et al.[25] suggested that the effect of contraction speed was not on neuromuscular activation, but rather on the intrinsic property of contracting myofibers. Remarkably, the muscle activities and AT of the fast angular velocity were increased 3 to 4.8 times as compared with the slow velocity, which was similar to the rate of angular velocity increase. Humans recognize the demands of a certain task and perform the required action using appropriate movement strategies.[17] Faster moments require more motor unit recruitment and increased utilization of fast-twitch fibers, resulting in higher EMG amplitudes.[26] This hypothesis is based on increased effort and the need for greater force output for higher angular velocities. The study participants had increased muscle activity in response to the increased demand for movement angular velocity; therefore, it is thought that angular velocity and AT also increased at a similar rate.

Previous studies on isokinetic movement reported that higher angular velocity was accompanied by decreased torque and working value and increased power.[5-11] Interestingly, as compared with the slow demand, the PT and TW of the fast movement request increased 7.8 and 13.8 times in this study. Considering mechanics, acceleration represents the rate at which the angular velocity of an object changes with time, which is given by the direction of the net force acting on that object. As described by Newton's second law, the magnitude of acceleration is proportional to the net balance of all external forces acting on that object and inversely proportional to the object's mass. A positive definite external force is torque resulting from muscle contraction and an opposing external force is the sum of the forces that impede movement (gravitational acceleration, friction, etc.).[18] In physics, torque is the rotational equivalent of linear force, which represents the capability of a force to produce a change in the rotational motion of the body. Work is a measure of energy transfer that occurs when an object is moved over a distance by an external force, at least part of which is applied in the displacement direction. Therefore, it is related not only to muscular strength but also to the distance of the force.[18] Moreover, the increased rate in the work value can be explained by the flowing physical process. An increase in torque with an increase in demand for angular velocity consequently increases the net force, which in turn increases the velocity of the object. As the angular velocity increases during movement of the same distance, time decreases. The increased work value compared with torque is a double result for an increase in muscle contraction and a decrease in movement time. The PP and AP in the fast angular velocity condition were highly affected by the velocity increase, increasing by 41.1 times and 48.7 times, respectively. Power is defined as work (product of force and distance) divided by the unit of time.[27] A more notable change in power compared with work is that the power value increases in proportion to the decrease in time because of the increase in movement angular velocity. The inverse relationship between force and angular velocity has been consistently established for isoinertial knee extension movement.[12] In this inverse correlation, the maximum power is obtained at the optimal values of force and angular velocity.[28]

Kinetic variables resulting in higher angular velocity revealed a decrease in muscular strength, torque, and work.[6-12] Resistance training with faster lifting velocity produced greater numbers of repetitions at given intensities.[29] The results of conventional isokinetic movement studies with a fixed maximum angular velocity are insufficient to explain this phenomenon. The reason for the diversity of observations and conclusions is that subjects perform tasks in which the subject is defined identically in different ways.[30] For example, movements that differ only in the magnitude of the distance or inertial load are quantitatively different. The reason for the different results for the increase in angular velocity is that it depends on an individual's intrinsic myofiber properties.[27] Therefore, results for angular velocity obtained using the isokinetic exercise, fixing the maximum velocity with producing the maximum force, should consider velocity as a qualitative variable. To the best of our knowledge, this study is the first to identify kinetic data for increasing demands in terms of angular velocity. In this study, the subjects used their own optimal pattern for each demand. It is thought that the demand for movement angular velocity was influenced as a quantitative factor for the task.

This study has several limitations. First, angular velocity is a continuous variable. However, because this study acquired data for three self-selective angular velocities, a data deficit occurred among the groups. As a result, regression analysis, a parametric statistic, could not be applied. Moreover, further studies are necessary to investigate the results of the regression analysis on the refinement of neuromechanical parameters by acquiring data for various self-selective angular velocities. Second, antagonist muscle activity was not measured in this study. Although we aimed to determine the activity of agonist muscles, which play a primary role in movement, activation of antagonist muscles may play an important role in the magnitude of joint moments. In particular, the activity of these antagonist muscles may differ between males and females. Therefore, further investigation is needed into the level of antagonist muscle activation depending on self-selected movement angular velocity.

We discovered that angular velocity, muscle activity, and AT increased at similar rates with increasing demands for movement angular velocity. The work value increased more than these data did, with power increasing the most. Considering the results, we drew the following three conclusions. First, the change in the kinetic data for increasing movement demands angular velocity is based on the increased efforts focused on musculature to activate fast to quickly accelerate the limb and overcome inertia. Second, in the velocity-force relationship, as the angular velocity increases, force output decreases. However, in this study using self-selected (slow, moderate, fast) angular velocities, both angular velocity and force output increased simultaneously. This may be because the angular velocity of each individual in this study did not reach close to the individual's maximum velocity. Third, the power of the fast angular velocity request increased 40 times compared to the slow velocity request. The higher angular velocity within the self-selective velocity range can be considered to use a more efficient pattern. Clinically, when designing physical therapy interventions, it is suggested that faster velocities of movement may be a way to increase exercise efficiency despite the fact that it can be a more challenging task with increased effort.

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