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Association of the Explosive Strength of Knee Extensors with Skeletal Muscle Mass, Peak Torque, and Joint Angular Velocity

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Objective: This study aimed to investigate the association of explosive strength with muscle mass and muscle function measured using traditional methods such as peak torque (PT) and joint angular velocity (PAV).

Design: Cross-sectional study

Methods: Twenty-nine healthy adults (14 males and 15 females) participated in this study. Body mass index and appendicular skeletal muscle index (ASMI) were measured using bioelectrical impedance analysis. The explosive strength of the knee extensors was evaluated by measuring the rate of torque development (RTD) and rate of velocity development (RVD). RTD was analyzed by dividing it into early (0-50 ms) and late (100-200 ms) muscle contraction phases. In addition, PT and PAV were measured as traditional methods for assessing muscle function.

Results: According to regression analysis, PAV accounts for 24.7% and 66.9% of the variance of RTD 0-50 ($p = 0.006$) and RVD ($p < 0.001$), respectively. On the other hand, ASMI ($p = 0.035$) and isometric PT ($p = 0.001$) explained 49.2% of the RTD 100-200.

Conclusions: Early RTD is mainly predicted by PAV, which is thought to be a result of muscle fiber type. Therefore, PAV presents the possibility of an alternative method to evaluate explosive performance. Late RTD seems to be related to ASMI or isometric PT. The findings of this study are expected to contribute to musculoskeletal rehabilitation and evaluation in that they revealed factors contributing to early and late muscle contraction.

Key Words: Rate of torque development, Rate of velocity development, Muscle strength

Introduction

The skeletal muscle function is to generate forces to maintain posture, produce movements that influence activity, and consequently maintain health and contribute to functional independence [1, 2]. Muscle strength was defined as the maximum torque produced by a maximum voluntary contraction within a given condition [3]. It was possible to objectively measure muscle strength using the isometric contraction of muscles under static conditions, and then a method for measuring isokinetic muscle strength corresponding to dynamic muscle contraction was developed [2, 4, 5]. Until recently, muscle strength was evaluated using the isometric or isokinetic contraction of muscles in various fields related to human movement, and the peak torque (PT) generated under these contraction conditions is mainly recorded [6 ,7]. Absolute force production, measured by PT, is essential not only when performing sports and exercises, but also in daily activities such as rising from a chair and climbing stairs [6, 8–10].

Although measurements of skeletal muscle mass cannot specifically predict muscle strength or physical ability, it has been reported to correlate significantly with these variables [11–14]. Therefore, appendicular skeletal muscle mass (ASMM), which refers to the sum of the muscle mass of the arms and legs, is often

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used to indirectly evaluate muscle function. Muscle mass assessed using magnetic resonance imaging, computed tomography, bioelectrical impedance analysis (BIA), etc. can be related to changes in muscle strength, and accurate evaluation of skeletal muscle mass can have important applications in physiology, nutrition, and clinical medicine [12, 15]. Indeed, normalized ASMM, as well as muscle strength, are used as important indicators to evaluate sarcopenia along with handgrip strength [16]. Moreover, these methods are widely used due to their low cost and convenience [15].

Body movements in daily activities include velocity components, such as the acceleration phase, which requires a quick response to muscle contraction [17]. However, the traditionally used measurements of muscle strength (measured by PT) and muscle mass does not include information on the rate of muscle contraction [7]. Accordingly, the rate of torque development (RTD) is increasingly being evaluated in athletes, the elderly, and patients, as well as in healthy adults [18]. Explosive strength that rapidly increases torque during a short contraction time can be evaluated using RTD [19]. This may be essential for both highly trained athletes and older adults who need to maintain their postural stability from unexpected perturbations [18]. RTD has been reported to be more relevant to sport-specific and functional daily tasks and more sensitive to changes in neuromuscular function when compared to general maximal voluntary contraction strength [18]. That is, it is controlled by other physiological mechanisms [20]. Similarly, in isokinetic testing, the rate of velocity development (RVD), estimated as a time-velocity curve during the acceleration phase, is commonly used to evaluate the acceleration ability [21, 22]. The relationship between RVD and PT was reported to be weak, suggesting that the two variables capture different functional aspects of the muscle [22]. RTD and RVD were suggested to be more related to functional movement than other parameters of muscle function, and a more rapid decline with age was found [23, 24]. Thus, RTD and RVD have the potential to independently contribute to physical function and performance [7]. Moreover, peak angular velocity (PAV) assessment has recently been proposed as a method to evaluate lower extremity muscle function [25–27]. According to the results, it has been reported that joint maximum angular velocity during knee extension has a stronger correlation with mobility function than isometric strength [27]. However, few studies have investigated the relationship of muscle function assessed using PAV to RTD and RVD. Therefore, our study aimed to investigate the relationship between RTD and RVD with muscle strength, appendicular skeletal muscle index (ASMI), and PAV measured by traditional methods.

Methods

Participants

A cross-sectional study design was used to confirm the relationship explosive strength (RTD and RVD) with body mass index (BMI), ASMI, isometric PT, isokinetic PT, and PAV. The sample size required for this study was calculated using statistical software (G-Power 3.1.9.7, Düsseldorf, Germany). The sample size was calculated based on the analysis of the relationship between the RTD and influencing factors (correlation ρ H1 = 0.7, alpha error probability = 0.05, statistical power = 0.95) [28]. The minimum sample size was twenty participants.

Thirty-two young adults volunteered to participate in this study. They had no history of lower extremity or lower-back surgery and were free from physical injuries in the past 6 months. Individuals with cardiovascular, or neurological diseases, or conditions that could hinder the maximal application of effort were excluded. Written informed consent was obtained from all participants after explaining the study purpose and experimental design. They were also aware of their right to withdraw from this study. The Institutional Review Board of Sunmoon University approved this study (SM-202109-065-2), which was performed by the principles of the Declaration of Helsinki.

Experimental procedures

Body composition such as body mass and skeletal mass were measured using BIA (InBody 570, In Body, Seoul, Republic of Korea). In addition, to evaluate the muscle function of knee extensors, isometric, isokinetic, and isotonic (for PAV measurement) testing were conducted using a dynamometer (HUMAC NORM Testing and Rehabilitation System, CSMI Medical Solutions, Stoughton, MA, USA), respectively. All measurements were performed on the same day.

Outcome measures

In measuring body composition, the ASMM is the sum of the muscle masses of the arms and legs. Body mass and ASMM were each normalized by dividing by the square of the height. BMI (kg/m^2) and ASMI (kg/m^2) were used for data analysis.

RTD and RVD of knee extensors were measured in isometric and isokinetic modes of a dynamometer, respectively. PT in both contraction modes was also recorded. In isotonic mode, the PAV of knee extension was measured. The order of measurements in the three modes was randomly assigned to each participant. The dominant limb was selected as the limb used for kicking. The participant was seated in a dynamometer chair and the trunk and thigh were secured using straps. The hip joint angle was maintained at 85° flexion. The rotation axis of the dynamometer was aligned with the knee lateral epicondyle and the force pad (padded arm) was placed approximately 3 cm above the medial malleolus. Participants first performed a warm-up consisting of 3 minutes of aerobic exercise using a cycle ergometer (power output of 1 Watt/kg and a crank rate of 60 revs/min) and ten incremental submaximal voluntary contractions of the knee extensors in each contraction mode [29]. All signals in all three modes were sampled at 100 Hz.

In isometric testing, knee joints were flexed at 70°, and the arms were held on both sides of the bar [30]. After two practice trials, participants were asked to perform isometric knee extensions of the dominant limb for 3 s with verbal instructions to push as fast and as hard as possible [7, 18]. Participants completed three trials and the PT and RTD values from the trial with the highest PT were selected for analysis [7]. PT (Newton meters, Nm) was represented as the maximum value of the torque released by a muscle contraction and normalized to body weight (Nm/kg) [31]. RTD (Nm/s) was defined as the slope of the torque-time curve (Δtorque/Δtime) [7, 18, 19, 30]. The point at which the force increased to more than 2.5% of each individual PT was determined as the onset of muscle contraction [18]. RTD values (1) 0 to 50 milliseconds (0-50 ms) and (2) 100 to 200 milliseconds (100-200 ms) were used for analysis.

For isokinetic testing, the knee range of motion was set from 90° flexion to 0° (knee full extension in voluntary). After two practice trials, participants were required to perform three knee concentric extensions at an angular velocity of 240 °/s with verbal encouragement from the investigator. In the isokinetic test, 240 °/s is mainly regarded as a high angular velocity, so it was used to measure muscle function at high velocity in this study [21]. PT (Nm/kg) and RVD values were calculated. The PT and RVD values of the trial with the highest PT values were used for analysis [23, 24]. RVD (°/s/s) represents the linear slope of the velocity-time curve (Δvelocity/Δtime). For RVD calculation, the start of movement of the knee joint was regarded as the point where the angular velocity reached 2 °/s, and the point was analyzed up to the point where it reached 2°/s below the target angular velocity (240 °/s) (i.e. from 2 °/s to 238 °/s) [24].

Contraction in the isotonic mode of knee extensors was used to measure the knee extension PAV. The knee range of motion was set to be the same as for isokinetic testing (90° flexion to 0°). Participants were asked to perform a concentric extension of the knee with verbal instruction to as fast as possible (no resistance except for the pad on the dynamometer). After two practices, three test trials were measured and the highest PAV (°/s) value was used for analysis.

Statistical analysis

All measured values are expressed as mean and standard deviation. The Shapiro–Wilk test was used to test the normality of the data. The two-tailed Pearson product-moment correlation coefficients were used to analyze the correlation of RTD and RVD of knee extensors with BMI, ASMI, knee extensor PT, and knee extension PAV. Pearson correlation coefficients (r) were interpreted as weak ($<$0.40), moderate (0.40 - 0.59), strong (0.60 - 0.79), and very strong ($>$0.80)

[32]. Multiple and stepwise linear regression was used when multiple independent variables that might explain the dependent variable (RTD or RVD). The level of statistical significance was set as $p < 0.05$. All procedures were performed using SPSS software (SPSS 22.0, Armonk, New York, USA).

Results

A total of 32 participants were recruited for this study, and data obtained from 29 participants (14 males and 15 females) were used for analysis. Three participants were dropped out due to the occurrence of knee pain (n = 1) and loss of data (n = 2). The physical characteristics of the participants are presented in Table 1.

Table 2 presents the correlation of RTD 0-50, RTD 0-100, and RVD with BMI, ASMI, and knee extensor muscle function. RTD 0-50 showed a weak positive correlation with BMI (r = 0.374, $p = 0.046$) and AMSI (r = 0.391, $p = 0.036$) and a moderate positive correlation with isometric PT (r = 0.439, $p = 0.017$) and PAV (r = 0.497, $p = 0.006$). RTD 100-200 had a moderate positive correlation with ASMI (r = 0.494, $p = 0.006$) and PAV (r = 0.533, $p = 0.003$), and a strong positive correlation with isometric PT (r = 0.629, $p < 0.001$). RVD was found to have a strong positive correlation with BMI (r = 0.679, $p < 0.001$), ASMI (r = 0.774, $p < 0.001$), and isokinetic PT (r = 0.755, $p < 0.001$), and a very strong correlation with PAV (r = 818, $p < 0.001$), respectively. Multiple linear regression models were calculated only for variables that showed significant correlations in the Pearson correlation test.

The results of multiple linear regression analysis for RTD 0-50 (dependent variable) are shown in Table 3. In regression model 1 (enter strategy), BMI, ASMI, isometric PT, and PAV did not influence RTD 0-50 ($p > 0.05$). According to regression model 2 (stepwise strategy), PAV accounts for 24.7% of the variance of

Table 1. General characteristics of participants

Variables	Total (n = 29)	Male (n = 14)	Female (n = 15)
Age (years)	24.10 ± 2.70	25.43 ± 1.74	22.87 ± 2.90
Height (cm)	168.29 ± 8.68	174.83 ± 5.80	162.18 ± 5.89
Body weight (kg)	63.99 ± 10.43	71.91 ± 7.07	56.60 ± 7.07
Body mass Index (kg/m^2)	22.48 ±2.51	23.59 ± 2.65	21.44 ± 1.91

Data are presented as mean ± standard deviation

Table 2. Correlation of RTD 0-50, RTD 100-200, and RVD with BMI, ASMI, and knee extensor muscle function

Variables (n = 29)		BMI (kg/m^2)	ASMI (kg/m^2)	Isometric PT (Nm/kg)	Isokinetic PT (Nm/kg)	PAV (°/s)
RTD 0-50 (Nm/s)	r	0.374	0.391	0.439	0.330	0.497
	p	**0.046***	**0.036***	**0.017****	0.081	**0.006****
RTD 100-200 (Nm/s)	r	0.336	0.494	0.629	0.342	0.533
	p	0.074	**0.006****	**< 0.001*****	0.069	**0.003****
RVD (°/s/s)	r	0.679	0.774	0.354	0.755	0.818
	p	**< 0.001*****	**< 0.001*****	0.059	**< 0.001*****	**< 0.001**†

Significant differences are presented in bold

* weak, ** moderate, *** strong, † very strong correlations

RTD: rate of torque development, RVD: rate of velocity development, BMI: body mass index, ASMI: appendicular skeletal muscle index, PT: peak torque, PAV: peak angular velocity

Table 3. Multiple regression analysis for variables predicting the RTD 0-50 (n = 29)

Independent variables	R²	Adjusted R²	B (SE)	Beta	t	*p*
Model 1 (Enter strategy)			F = 2.753, *p* = 0.051			
	0.315	0.200				
BMI			23.815 (33.163)	0.170	0.718	0.480
ASMI			2.216 (90.297)	0.007	0.025	0.981
Isometric PT			179.202 (120.261)	0.299	1.490	0.149
PAV			1.944 (2.800)	0.236	0.695	0.494
Model 2 (Stepwise strategy)			F = 8.875, *p* = 0.006			
	0.247	0.220				
PAV			4.097 (1.375)	0.497	2.979	0.006*

*$p < 0.01$

RTD: rate of torque development, BMI: body mass index, ASMI, appendicular skeletal muscle index, PT: peak torque, PAV: peak angular velocity

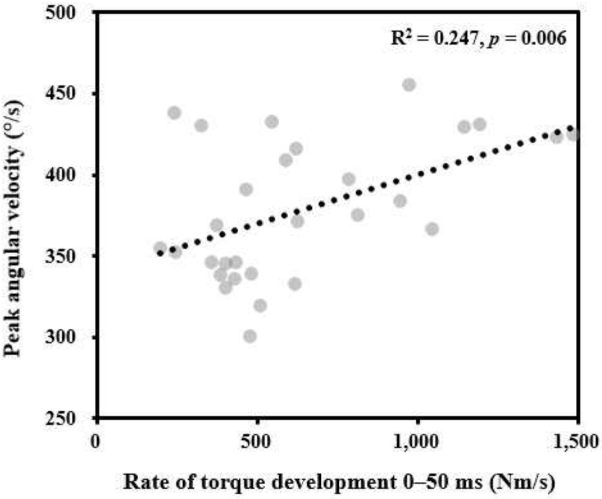

Figure 1. Relationship between rate of torque development 0-50 and peak angular velocity in knee extension

RTD 0-50. The regression equation was $y = 4.097x - 911.961$ ($p = 0.006$) (Figure 1).

Multiple linear regression (enter strategy, model 1) was performed to predict RTD 100-200 (dependent variable) from ASMI, isometric PT of knee extensors, and PAV in knee extension (Table 4, Figure 2). Regression model 1 explained 49.4% of the variance for RTD. Among the independent variables, only isometric PT significantly predicted RTD 100-200. The regression equation as follows: $y = 168.652x - 412.599$ ($p = 0.005$). However, no significant association was found between RTD 100-200 with ASMI and PAV ($p > 0.05$). Stepwise multiple regression analysis (model 2, Table 4 and Figure 2) showed that RTD 100-200

Table 4. Multiple regression analysis for variables predicting the RTD 100-200 (n=29)

Independent variables	R²	Adjusted R²	B (SE)	Beta	t	*p*
Model 1 (Enter strategy)			F = 8.127, p = 0.001			
	0.494	0.433				
ASMI			49.392 (41.631)	0.281	1.186	0.247
Isometric PT			168.652 (54.153)	0.509	3.114	0.005**
PAV			0.295 (1.166)	0.065	0.253	0.802
Model 2 (Stepwise strategy)			F = 17.690, $p < 0.001$			
	0.396	0.373				
Isomeric PT			208.405 (49.550)	0.629	4.206	< 0.001**
Model 3 (Stepwise strategy)			F = 12.613, $p < 0.001$			
	0.492	0.453				
ASMI			57.559 (25.874)	0.328	2.225	0.035*
Isomeric PT			174.112 (48.781)	0.526	3.569	0.001**

*$p < 0.05$; **$p < 0.01$

RTD: rate of torque development, ASMI, appendicular skeletal muscle index, PT: peak torque, PAV: peak angular velocity

Table 5. Multiple regression analysis for variables predicting the RVD (n=29)

Independent variables	R²	Adjusted R²	B (SE)	Beta	t	*p*
Model 1 (Enter strategy)			F = 18.747, $p < 0.001$			
	0.758	0.717				
BMI			6.036 (3.038)	0.291	1.987	0.058
ASMI			10.365 (8.211)	0.221	1.262	0.219
Isokinetic PT			50.788 (32.710)	0.316	1.553	0.134
PAV			0.224 (0.299)	0.184	0.747	0.462
Model 2 (Stepwise strategy)			F = 54.466, $p < 0.001$			
	0.669	0.656				
PAV			0.993 (0.135)	0.818	7.380	< 0.001*

*$P < 0.01$

RVD: rate of velocity development, BMI: body mass index, ASMI, appendicular skeletal muscle index, PT: peak torque, PAV: peak angular velocity

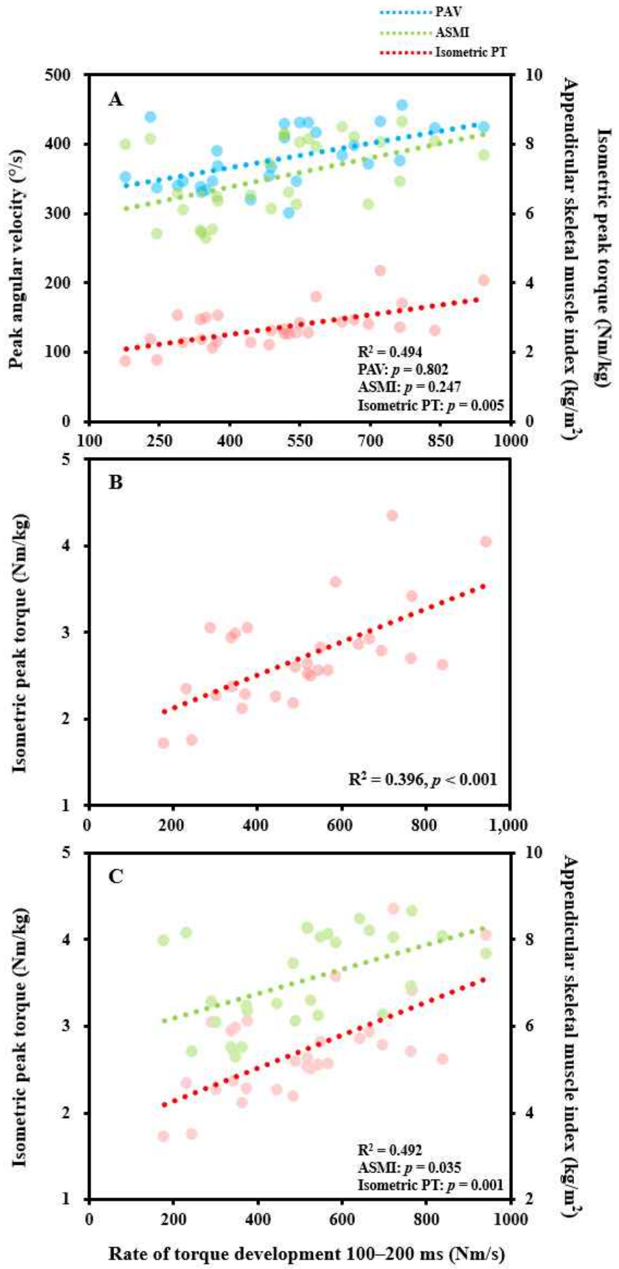

Figure 2. Relationship of the rate of torque development 100-200 with (A) peak angular velocity in knee extensors, (B) isometric PT of knee extensors, and (C) ASMI and isometric PT of knee extensors

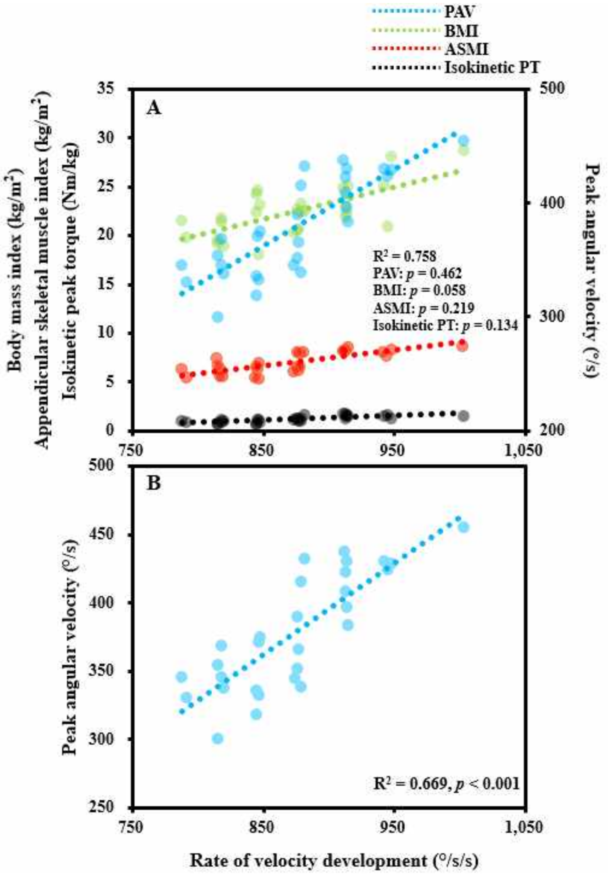

Figure 3. Relationship of the rate of velocity development with (A) peak angular velocity (PAV) in knee extension, body mass index, appendicular skeletal muscle index, and isokinetic peak torque of knee extensors and (B) PAV in knee extension

was best predicted by isometric PT. According to this analysis, 39.6% of the variance for RTD 100-200 could be accounted for by isometric PT ($y = 208.405x - 60.304$, $p < 0.001$). The model 3 containing ASMI ($y = 57.559x - 373.228$, $p = 0.035$) and isometric PT ($y = 174.112x - 373.228$, $p = 0.001$) explains 49.2% of the RTD 100-200 (model 3, Table 4 and Figure 2).

Table 5 presents the results of multiple linear regression analysis for RVD (dependent variable). In Model 1 (enter strategy), BMI (regression equation: $y = 6.036x + 518.975$), ASMI (regression equation: $y = 10.365x + 518.975$), isokinetic PT (regression equation: $y = 50.788 + 518.975$) of knee extensors, and PAV (regression equation: $y = 0.224x + 518.975$) in knee extension accounted for 75.8% of the RVD variance ($p < 0.001$) (Figure 3). However, each variable did not influence RVD ($p > 0.05$). In the stepwise multiple regression model (model 2), 66.9% of the variance in the RVD was predicted by PAV ($y = 0.993x + 497.914$, $p < 0.001$) (Figure 3).

Discussion

This study investigated the relationship between RTD and RVD of knee extensors with muscle strength, ASMI, and PAV measured by traditional methods. The findings of this study were that PAV was a main contributing factor for RTD 0-50 and RVD. On the other hand, isometric PT and ASMI were the main contributors to RTD 100-200.

RTD 0-50 correlated with BMI, ASMI, isometric PT, and PAV. In the regression analysis, PAV (accounting for 13.4% of the variance) was the only main predictor of RTD 0-50. In addition, RVD was found to be correlated with most variables and PAV was identified as the main predictor (accounting for 66.9 % of the variance). The increase in torque up to 50 ms after the onset of muscle contraction refers to the ability to generate torque rapidly [33]. RVD can be defined as the time required to reach a predetermined angular velocity as a measure of the ability to accelerate during initial muscle contraction [21]. RVD appears to be related to the ability to generate force as rapidly as it reflects the ability to accelerate early in muscle contraction [21]. On the other hand, RTD 100-200, corresponding to the late phase of RTD, were predicted by isometric PT and ASMI (accounting for 49.2% of the variance). Stepwise regression analysis showed that isometric PT was the best predictor (accounting for 39.6% of the variance). RTD is often classified into early and late phases according to time intervals [18, 20]. Indeed, several studies have investigated factors influencing the early and late phases of RTD [18, 19, 20, 28, 34, 35]. In this study, up to 50 ms after the onset of muscle contraction and 100-200 ms were considered early and late RTD, respectively. The results of this study suggest that different factors may influence RTD 0-50 or RVD and RTD 100-200, respectively.

In studies that identified the relationship between maximal strength and RTD, it was reported that there was a moderate to strong relationship [36]. However, studies have been reported that found no change in RTD despite an increase in maximal strength after resistance training [37, 38]. Moreover, although maximal strength increased after resistance training, there was no change in the acceleration of unloaded knee extension [39]. Considering the inconsistency of these previous studies, explosive strength (RTD or RVD) and maximal strength may each be affected by different factors. Andersen et al. [20] suggested that the discrepancy results mentioned above could be explained by the time interval used when analyzing RTD. That is, they reported that approximately 80% of RTD variance during the late phase (150-250 ms) was explained by maximal strength, while RTD during the early (< 50 ms) was moderately related to maximal strength [20]. In addition, late RTD was found to be positively correlated with muscle thickness in the vastus lateralis and vastus intermedius. Recently, Cossich and Maffiuletti [28] reported that compared with early RTD, late RTD was correlated with maximal quadriceps muscle strength and muscle mass. Therefore, they suggested that quadriceps mass, as well as maximal strength, was the main determinant of the late RTD of knee extension [28]. These results are more supportive considering that the time taken to generate explosive force is limited (< 50-250 ms), whereas a long time (> 300 ms) is required to reach maximum strength [20, 34]. In our results, the main predictors of RTD 100-200 were isometric PT and ASMI. Therefore, our study partially supports the results of previous studies. Because early RTD is not predicted by commonly used muscle strength and mass measurements, it may need to be evaluated with tests other than these methods. Moreover, the findings of this study support the opinion that both should not be presented due to the redundancy of late RTD and maximum torque, as presented in previous studies [28].

Several recent studies have found that early RTD is primarily influenced by neural drive. Electromyography studies have reported that nerve drive to muscles has a very significant effect on the initial contractile phase [33]. The early RTD was correlated with muscle activity in the quadriceps, and the correlation coefficient decreased with time [28]. A causal association between RTD and initial motor unit discharge rate and recruitment speed was identified, especially for the first 35 - 40 ms activity [35]. Based on these results, Cossich and Maffiuletti [28] confidently suggested that motor unit behavior during explosive contraction is the main determinant of early RTD. Del Vecchio et al. [35] emphasized the role of the central nervous system, suggesting that the initial nerve drive to the muscle before the onset of force may have determined the generation of the explosive force. They showed the effect of cortical input on motor neurons without the afferent feedback generated by the muscle in the early stages of the motor task. In other words, they concluded that corticospinal input intensity influences the ability to generate force rapidly [35].

In our findings, the main predictor of early RTD or RVD was PAV. Since neuronal activation was not investigated in this study, it cannot be explained whether there was an effect of the previously mentioned nerve drive. Nevertheless, one noteworthy point is that more discharges per motor unit per second were associated with faster motor unit recruitment, which was associated with early RTD [35]. As a result of the increased discharge rate, faster recruitment of motor units containing type II fibers with higher thresholds is possible and consequently ensures a faster rise in force [18, 40]. Although no direct measurements of muscle fiber type were performed in this study, in the evaluation of the PAV (unloaded concentric knee extension), participants were instructed to 'as fast as possible, as strong as possible' and verbal encouragement was provided. It is also well known that faster fibers (type II) are more recruited for faster work [41]. Therefore, it is predicted that the PAV values obtained from participants may indirectly reflect the rapid recruitment of type II fibers (or the relative proportion of type II fibers). Since type II fibers are less sensitive to calcium than type I fibers and release more Ca^{2+} per action potential, the increase in force per action potential is greater in type II fibers [18, 42]. In addition, the rate of cross-bridge formation is Ca^{2+} dependent, so type II fibers are 3 to 8 times faster than type I fibers [18, 42]. Furthermore, type II fibers conduct action potentials better due to their higher discharge rates, as they have 200 - 300% higher Na^{+} channel density [43]. For this reason, an increase in nerve drive to a muscle with a greater proportion of type II fibers may have a substantial influence on RTD [18]. Indeed, it has been suggested that the initial RTD may decrease as fiber types of transition from IIX to IIA fibers [34]. Their multiple regression results reported that reduced type IIX fiber accounted for 38% of the reduction in early RTD. Type II fiber may be particularly important for mechanical muscle output in the early phases of muscle contraction, and in this regard, a positive correlation was observed between peak RTD and percent IIX fiber area [19]. The reason PAV measured in this study was found to be the main predictor of RTD 0-50 (or RVD) is probably because type II fibers have in common that they contribute importantly to both PAV and RTD 0-50. The finding that resistance training performed with the highest possible acceleration can increase early RTD seems in line with the findings of this study [44]. Because the PAV is more convenient than RTD measurements, it can be considered an alternative method for evaluating initial muscle contraction (RTD 0-50). Further research is needed in this regard.

Conclusion

Early RTD is mainly predicted by PAV, which is thought to be a result of muscle fiber type. Therefore, PAV presents the possibility of an alternative method to evaluate explosive performance. Late RTD seems to be related to ASMI or isometric PT. It is predicted that this is mainly because the time point at which PT occurs is closer to the late phase in the RTD time interval. Although this study has a limitation in that the differences in muscle properties by sex were not considered, the findings of this study are expected to contribute to musculoskeletal rehabilitation and evaluation in that they revealed factors contributing to early and late muscle contraction.

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