Original Article

Journal of Wellness and Health Care Vol.43(1)
47～53 2019

Prediction of maximum isometric muscle strength of knee extensors using ultrasonography

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Abstract

Muscle echo intensity (EI) determined by ultrasonography has recently been reported as an index of intramuscular fat. The muscle thickness (MT) and EI of the quadriceps femoris muscle were reported to be influenced by the muscle strength (MS) of the knee extensors. This study was performed to investigate whether the MT and EI of the quadriceps femoris are associated with the MS of knee extensors, and to establish a predictive formula for the maximal isometric MS of knee extensors.

Forty healthy volunteers 20-59 years old were included in this study. The maximal isometric MS of knee extensors on the dominant extremity was measured at knee flexion of 60°, and was defined as the maximal value over three repeated measurements. Transverse ultrasound images of the quadriceps on the dominant extremity were obtained with a B-mode ultrasound imaging device and multi-frequency linear transducer. During measurements, the participants were completely relaxed and sat comfortably with the knee flexed at 90°. A 10-MHz transducer with gain of 58 dB was used during all measurements. The transducer was positioned perpendicular to the longitudinal axis of the quadriceps femoris, at the midpoint between the anterior superior iliac spine and the proximal end of the patella. The same investigator then obtained three consecutive images. The subcutaneous fat thickness, MT of each muscle, and EI of each muscle were analyzed from three images acquired for the rectus femoris (RF) and vastus intermedius (VI), and the mean values of the three measurements were recorded. Pearson's and Spearman's correlation coefficients were calculated to investigate the relationships between subcutaneous fat thickness, MT, EI, physical characteristics, and MS. Stepwise multiple regression analysis was then performed with MS value as the dependent variable, and the characteristics of the participants and values from the ultrasound images as independent variables. In addition, multiple regression analysis was performed in two groups divided according to age, i.e., the young adult group and the middle-aged group.

There were no significant differences in height, weight, BMI, or muscle circumference between the young adult group and middle-aged group. MS showed significant negative correlations with subcutaneous fat thickness, RFEI, and VIEI, and significant positive correlations with height, weight, circumference, RFMT, and VIMT. Stepwise regression analysis identified height and VIMT as factors significantly associated with MS (adjusted $R^2 = 0.65$). Height and VIMT contributed to MS in young and middle-aged individuals.

KEY WORDS

Ultrasonography, Muscle strength, Muscle thickness, Echo intensity, Quadriceps femoris

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Introduction

In recent years the aging of the world population has been progressing rapidly at an unparalleled rate in the past[1]. Rehabilitation for the health promotion or prevention of disease for elderly has become common[2]. It is often experienced in clinical practice that elderly people have to stay rest due to their treatment of disease or trauma and their activity declines, and it makes them difficult to walk indecently and reduces their level of activities of daily living by causing so-called disuse syndrome.

Muscle strength (MS) of knee extensor is known as an important index for walking ability and independence of life[3]. It is reported that not only the ability for walking but also the independence of living decreases when the MS of knee extensor is not enough[4]. Thus, the measurement or evaluation of the MS of knee extensor is important. On the other hand, there is a lot of elderly who complain knee pain during exercise, due to such as osteoarthritis of knee joint, and those who have severe dementia. In those cases, it is often difficult to measure their MS correctly.

In recent years, due to the widespread use of inexpensive and non-invasive ultrasound imaging diagnostic apparatuses, muscle volume can be evaluated easily and safety in clinical practice. The utility of muscle echo intensity (EI) has been drawing attention as a method for evaluating intramuscular fat quality using ultrasonography. Muscle EI indicates as an index of intramuscular fat and/or fibrosis tissue. While anatomical factors of quadriceps femoris muscle such as muscle thickness (MT), pennation angle, and muscle cross-sectional area affect the MS[5-7], there have been reported some studies about the correlations with MS and EI[8-10]. However, the correlation coefficients are not consistent. One of the reasons is that there are wide range in EI between younger population and middle aged people[8]. While younger people do not have wide variation compared with senior or elderly people in EI, middle-aged people of EI have wide difference due to their aging effect, physical activity, and muscle quality. Furthermore, some studies investigated only the relationships between MS and findings from ultrasound, the other studies targeted quite a narrow generation as subjects. There still have been few studies predicting MS with higher accuracy.

The aims of the study were (1) to establish a formula for predicting the maximal isometric MS of knee extensors from the physical characteristics and findings from ultrasonography in healthy subjects of a wide range of age and (2) to compare factors influencing the maximal isometric MS of knee extensors in young adult and middle-aged subjects.

Methods

1. Participants

Forty-two healthy volunteers (years; range, 20-59 years) were enrolled in this study (20 male and 20 female). Participants with previous history of surgery of the trunk or lower limb; neurological or musculoskeletal disorders were excluded. Table 1 shows the characteristics of subjects. All subjects provided written informed consent. The study protocol was approved by the ethics committee of our institution.

Table 1 Characteristic of the subjects (mean ± SD)

Characteristic	Value
Age (years)	38.7 ± 11.6
Height (cm)	165.9 ± 7.6
Weight (kg)	58.8 ± 10.1
BMI (kg/m^2)	21.2 ± 2.4
Thigh circumstance (cm)	50.2 ± 4.4

SD = standard deviation; BMI = body mass index.

2. Ultrasound measurement

Firstly, we first measured the height, weight, and thigh circumference for the subjects. The circumference of the thigh was measured at the midpoint position of the straight line connecting the anterior superior iliac spine and the proximal end of the patella of dominant lower limb.

Secondly, transverse ultrasound images of the anterior part of the thigh on the dominant lower extremity were obtained using a B-mode ultrasound imaging device (LOGIQ P5; GE Healthcare Japan, Tokyo, Japan) with 10-MHz linear transducer. During measurements, the participants were completely relaxed and sat comfortably, with the knee flexed at 90 degrees. Measurement site for the rectus femoris (RF) and vastus intermedius (VI) muscle was the midway between the anterior superior iliac spine and the proximal end of the patella[11]. A 58-dB gain was used during all measurements. To ensure that the transducer pressure was kept to a minimum for avoiding the distortion of the skin and subcutaneous tissue caused by excessive compression, a sufficient amount of contact gel was used to the skin. The same investigator then obtained 3 consecutive images.

Thirdly, the MT and EI of RF and VI were measured using those images with Image J (National Institute of Health, Bethesda, MD, USA) (Figure 1). The subcutaneous fat thickness (FT) as the distance between the upper boundary of the ventral fascia and the line separating the dermis from fat was also measured. The mean values of the 3 measurements were used for statistical analysis. Regions of interest were selected at a depth of 7.0 cm avoiding the surrounding fascia. EI were investigated by 8-bit gray-scale analysis using the histogram function in Image J. The mean EI of the regions was expressed in values between 0 and 255 (0: black; 255:white).

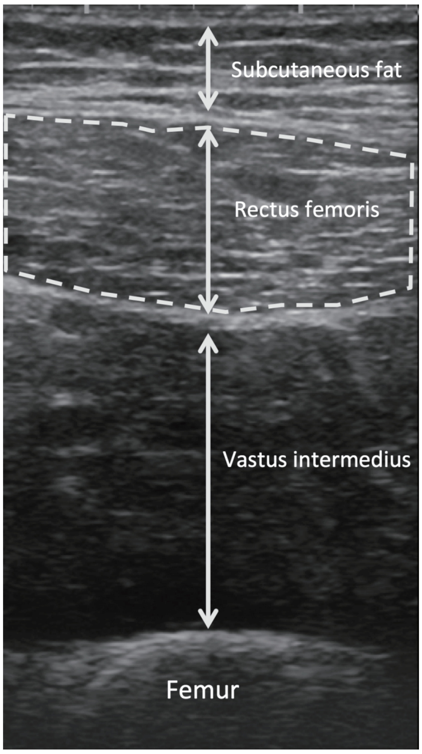

Figure 1 Transverse ultrasound image of the anterior part of thigh
The double-headed arrows indicate the length of muscle thickness.
The region enclosed by the dashed lines indicates the region of interest for echo intensity.

Prior to data acquisition, the ultrasound examiner established inter-tester reliability by assessing 7 participants with the same inclusion/exclusion criteria as used in this study. Intra-class correlation coefficients (ICC) (1.1) were evaluated using two images taken on two separate days. The ICC (1.1) for the MT and EI measurement were ranged from 0.95 to 0.81 and from 0.90 to 0.78, respectively.

3. Muscle strength measurement

The maximal isometric MS of knee extensors was measured using a muscle force measuring device Combit CB-2 (Minato Medical Science Co., Ltd., Osaka, Japan) at a hip flexion angle of 90 degrees and a knee flexion angle of 60 degrees. Both upper limbs were kept crossed in front of the trunk. The maximal isometric MS of knee extensor was measured for 3 seconds separated by a 60 seconds rest period, and it was repeated 3 times and the highest MS was used for analysis.

4. Statistical analyses

Pearson or Spearman correlation coefficients were calculated to investigate the relationships between MT, EI, physical characteristics, and MS.

Stepwise multiple regression analysis was performed to establish a predictive formula for the maximal isometric MS of knee extensors. Independent variables that showed significant correlations with MS by Pearson or Spearman correlation tests were used as dependent variables. To monitor for a multicollinearity effect, the variance inflation factor (VIF) was calculated. A model was considered ill conditioned if the VIF was higher than 10[12]. Furthermore, in order to compare the differences in factors affecting MS between young adult and middle-aged, subjects were divided at the mean age (38.5 years) into young adult groups and middle-aged group. Multiple regression analysis was then performed in the same way. Statistical analysis for this study was performed using the Statistical Package for the Social Sciences (SPSS) for Windows version 23.0 (SPSS Inc., Chicago, IL, USA). Significance was accepted at a level of $p<0.05$.

Results

There were no significant differences between two groups in height, weight, BMI, and circumference (shown in Table 2). Table 3 shows the ultrasound measurements of the subjects. MS showed a significant negative correlation with FT, RFEI, and VIEI, and a

Table 2 Comparison of characteristic between two groups (mean ± SD)

Characteristic	Young adult group	Middle-aged group	P value
Age (years)	29.2 ± 5.5	49.2 ± 6.2	<0.01
Height (cm)	167.9 ± 7.6	163.6 ± 7.2	0.08
Weight (kg)	59.0 ± 11.2	58.5 ± 9.2	0.87
BMI (kg/m^2)	20.8 ± 2.4	21.7 ± 2.3	0.19
Thigh circumstance (cm)	51.1 ± 4.7	49.3 ± 4.1	0.21

SD = standard deviation; BMI = body mass index.

Table 3 Ultrasound measurements of the subjects (mean ± SD)

Measurements	Value
FT (cm)	0.54 ± 0.25
MT of RF (cm)	1.87 ± 0.42
EI of RF	71.9 ± 14.0
MT of VI (cm)	2.02 ± 0.51
EI of VI	54.7 ± 11.9

SD = standard deviation; FT = subcutaneous fat thickness ; MT = muscle thickness; RF = rectus femoris; EI = echo intensity; VI = vastus intermedius.

Table 4 Correlation coefficients between characteristics, FT, MT, EI, and the muscle strength of the participants (n = 40)

	Age	Height	Weight	BMI	TC	FT	RFMT	RFEI	VIMT	VIEI	MS
Age	-	-0.29	-0.20	0.11	-0.32**	-0.04	-0.25	0.37*	-0.27	0.46**	-0.27
Height		-	0.80**	0.41**	0.54**	-0.38*	0.68**	-0.54**	0.45**	-0.53**	0.74**
Weight			-	0.85**	0.82**	-0.16**	0.71**	-0.41**	0.61**	-0.63**	0.73**
BMI				-	0.81**	0.22	0.50**	-0.14	0.55**	-0.54**	0.49**
TC					-	0.25	0.59**	-0.32*	0.69**	-0.72**	0.57**
FT						-	-0.34*	0.44**	-0.13	-0.02	-0.39*
RFMT							-	-0.67**	0.39*	-0.64**	0.58**
RFEI								-	-0.23	0.43**	-0.44**
VIMT									-	-0.74**	0.64**
VIEI										-	-0.67**
MS											-

BMI = body mass index, TC = thigh circumstance, FT = subcutaneous fat thickness, RFMT = muscle thickness of rectus femoris, RFEI = echo intensity of rectus femoris, VIMT = echo intensity of vastus intermedius, VIEI = echo intensity of vastus intermedius, MS = muscle strength.
Statistical significance: * P<0.05, ** P<0.01

Table 5 Regression equations for muscle strength of knee extension prediction

	Equations	R	adjusted R^2	N
All subjects	-585.08+3.95×height (cm)+40.55×VIMT (cm)	0.82	0.65	40
Young adult	53.33-56.14×sex+2.39×weight (kg)	0.83	0.66	21
Middle-aged	70.50+2.46×weight (kg)-1.05×RFEI	0.87	0.73	19

VIMT = echo intensity of vastus intermedius, sex: male =0, female = 1; RFEI = echo intensity of rectus femoris,

significant positive correlation with height, weight, BMI, thigh circumference, RFMT, and VIMT (Table 4).

Through multiple regression analysis with the height and VIMT as independent variables, the formula for predicting the maximal isometric MS of knee extensors was created as follows: -585.08 + 3.95 × height (cm) + 40.55 × VIMT (cm). The coefficient was R^2=0.65 (Table 5). The F value was less than 1% in the estimation formula ($p<0.01$). The average residual was 24.7 Nm. There was no residual correlation between the height and VIMT. The VIF value was 1.25.

After dividing into two groups at the median age, stepwise multiple regression analysis for young adult group showed that sex and weight were predictors for MS. On the other hand, stepwise multiple regression analysis for middle-aged group revealed that weight and RFEI were predictors for MS (Table 5).

Discussion

The main result of the study is that we can predict the maximal isometric MS of knee extensors with relatively high accuracy by measuring their height and VIMT using ultrasonography. Improvement of the function of antigravity muscles is essential for enhancing the walking ability of frail elderly people. For prescribing their exercise program and evaluating the effect of treatment, it is useful to measure MS of knee extensor. Hospitalized patients are often forced to lie down and to stay rest to be treated diseases or trauma. Elderly people with knee osteoarthritis often complain knee pain during knee exercise. Patients with cardiovascular disease sometimes have to refrain Valsalva maneuver. Therefore, the measurement of maximum MS of knee extensor is often difficult because they cannot perform maximum muscle contraction. If we estimate the maximum MS without doing maximal muscle contraction for such subjects, we may safely evaluate usability about programs for musculoskeletal function improvement, and it will be useful in clinical practice of rehabilitation.

Previous studies showed that MS could be predicted using MT[13]. However, the accuracy was not enough high due to lack of considering their physical characteristics. We could create better formula for estimating MS using both ultrasonography and physical characteristics with higher accuracy. Another previous study showed the height and weight is one of the indicators to predict MS[14] because higher height or weight indicates larger physical frame and greater muscle volume. Many studies have been reported that there is correlation between MT and MS[8,9,15]. Since MT is an important indicator reflecting the cross-sectional area of muscle fibers that affects MS, MS was predicted by MT[16]. The validity of the regression equation for all subjects seems to be high because the significance level of F value was less than 1%, the significance level of each variables in this regression equation were all less than 1%. Moreover, the value of VIF was only 1.25 and it means there was low possibility of multicollinearity effect. In residual analysis, the mean residual of isometric maximal MS of knee extensor was 24.7 Nm (16%) in this formula. Astrand[17] previously reported that the daily variance of MS was between 10 to 20 %. It indicates that the estimated regression equation in this study can be applied for healthy people from aged 20 to 59.

Another findings of this study were that there were differences in factors influencing the maximal isometric MS of knee extensors in young adult and middle-aged subjects. The predicators of MS were sex and weight in young adult group while the predicators were weight and VIEI in middle-aged group. It was suggested that the method of measuring the muscle EI might be useful to predict the MS prediction in middle-aged group. On the other hand, previous studies showed there was negative correlation between EI and MS as well as the results of this study[8,9]. According to Pillen et al.[18], EI increases from around 40 years old in both men and women. Fukumoto et al.[8] reported that EI of the quadriceps femoris muscle can be a predictor of maximum isometric MS of knee extensor in elderly women healthy volunteers and the results were similar to the results of this study. Furthermore, in previous studies using CT by Goodpaster et al.[19], there is correlation between damping coefficient of the thigh muscles and muscle weakness. Underlying reasons for increase of EI is upward the ratio of non-contractile tissue in muscles caused by such as intramuscular fat infiltration or fibrosis[20,21]. From these findings, it was thought that the decrease in quality of muscles such fatty or fibrotic degeneration in muscles mainly affected to MS in generations around over 40 years old.

There were still some limitations in this study. First, since the target muscle was only RF and VI muscle in the quadriceps femoris, this result cannot be applied to other skeletal muscle. Secondly, we can not apply the results of this study as they are to elderly healthy individuals or patients with diseases or trauma since the subjects were limited to healthy subjects between 20 and 59 years old. In order to verify the validity, this method should be confirmed in other muscles. Future researches are needed to apply the results of this study to elderly people or patients.

In this study, predictive equations for isometric MS of knee extension was created from physical characteristics and ultrasonic images in healthy subjects between the ages of 20 and 50. We found that there ware correlates between the MS of knee extension and the height, body weight, BMI, thigh circumference, subcutaneous FT, RFMT, RFEI, VIMT, and VIEI. Prediction equations for isometric MS of knee extensor calculated from the physical characteristics of the subject and ultrasonic image findings was as follows; $-585.08 + 3.95 \times$ height (cm) $+ 40.55 \times$ VIMT (cm). We clarified that the height and VIEI affect the MS of knee extension in young adult group. In particularly, the weight and RFEI contribute to MS of knee extension in middle-aged group.

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大腿四頭筋の超音波画像を用いた等尺性膝関節伸展筋力の推定

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要　旨

近年，超音波診断装置を用いた筋厚に加え筋内脂肪増加の評価方法として筋輝度の有用性が注目されている。本研究の目的は幅広い年代の健常者において，対象者の身体特性および超音波画像所見から等尺性膝関節伸展筋力の予測式を立案することである。

健常成人 40 名を対象とした。最大等尺性膝関節伸展筋力は筋力測定装置を用いて股関節屈曲 90°，膝関節屈曲 60°にて 3 回測定し，最大の値を筋力値とした。また超音波診断装置を使用し，上前腸骨棘と膝蓋骨底の中点にて大腿四頭筋の短軸画像を B モードにて撮影した。画像は 3 回撮影し，画像解析ソフトを用いて皮下脂肪厚，大腿直筋厚，中間広筋厚，および大腿直筋輝度，中間広筋輝度を計測した。対象者の筋力値と身体特性および超音波画像所見との関連性を Pearson の積率相関係数または Spearman の順位相関係数を用いて検討した。また筋力値を従属変数，他の有意な相関がみられた項目を独立変数とし，ステップワイズ法を用いて重回帰分析を行った。また，重回帰分析は若年者群と中高年者群でそれぞれ行われた。

若年者と中高年者の 2 群間で身長, 体重, MBI, 大腿周径に有意差は認めなかった。身長, 体重，BMI，大腿周径，皮下脂肪厚，大腿直筋厚，大腿直筋輝度，中間広筋厚，中間広筋輝度と相関があることが判明した。重回帰分析の結果，等尺性膝関節伸展筋力には対象者の身長および中間広筋厚が選択され，adjusted R^2=0.65 の統計学的に有意な回帰式を得た。本研究の結果より，身長と中間広筋厚が等尺性膝関節伸展筋力に寄与することが示唆された。