accordance with the Declaration of Helsinki. The participants and parents of the junior players were fully informed of the study procedures as well as the purpose of the study, and gave their informed written consent.

Measurement of muscle cross-sectional area

Magnetic resonance images were obtained separately for both thighs using a 0.2-T scanner (Signa Profile, General Electric Medical System) with a body coil to determine the cross-sectional area of the total muscle compartments (TMC) and quadriceps femoris (QF), hamstrings (Ham), and adductors (Add). First, longitudinal images were obtained to identify the greater trochanter and lower edge of the femur. Second, transverse scanning of T1-weighted images of 10 mm thickness was performed from the greater trochanter to the lower edge with a 10-mm gap (TR 350 ms, TE 21ms, matrix 256 × 256, field of view 40 × 40 cm, 2 NEX). Similar to the method of Masuda et al. (2003), images located nearest to 30% (proximal to the knee), 50%, and 70% of femur length, from the lower edge of the femur to the greater trochanter, were selected for the determination of cross-sectional area (Figure 1). For each of the transverse images, a single experienced observer, blinded to the participants' characteristics, outlined the areas of the total muscle compartment and three muscle groups – the quadriceps femoris (rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius), hamstrings (biceps femoris, semitendinosus, and semimembranosus), and adductors (adductor brevis, adductor longus, adductor magnus, and adductor minimus) – using a computer mouse. Cross-sectional area was then calculated by summing the pixels surrounded by the outlines. In addition to the absolute value, the cross-sectional areas of each of the three muscle groups and the sum of the hamstrings and adductors (Ham + Add) were expressed as the percentage of the total muscle compartment and are referred to as %QF, %Ham, %Add, and %Ham + Add, respectively. Intra-observer differences in the calculation of muscle cross-sectional area were addressed by repeating the measurements ten times in a pilot study with three young men. The coefficient of variation (%CV) for the determination of cross-sectional area was less than 1%.

Measurement of dynamic strength

Isokinetic torque during maximal concentric knee extension and flexion in both legs was determined using a dynamometer (Biodex System 3, Biodex Co., USA). For an appropriate evaluation of dynamic strength in soccer players, it is preferable to perform measurements over a wide range of angular velocities (Cometti et al., 2000; Leatt et al., 1987). However, this was impossible due to the limited time schedule of the study. Gur et al. (1999) reported that adult soccer players showed higher knee torque than

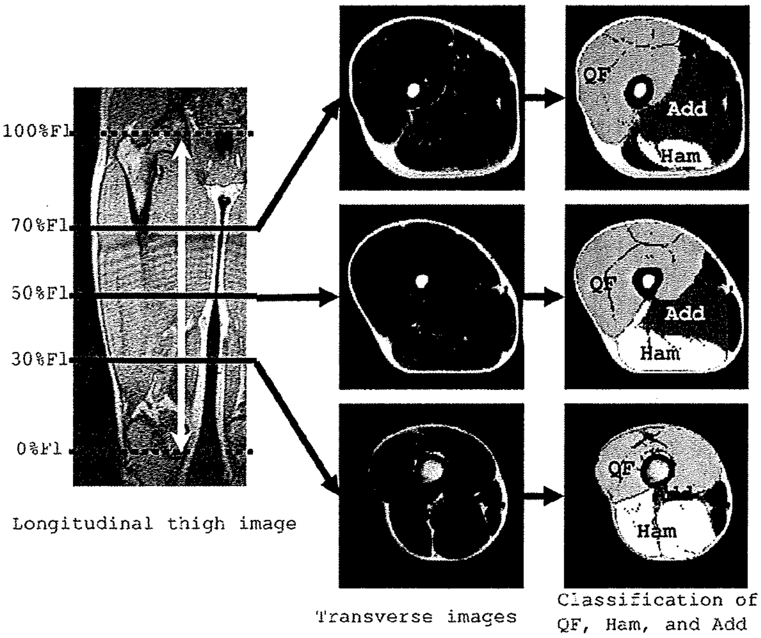

Figure 1. Sample transverse magnetic resonance images and classification of the three muscle groups at 30%, 50%, and 70% of femur length. Fl = femur length; QF = quadriceps femoris; Ham = hamstrings; Add = adductors.

younger players above 3.14 rad · s^{-1}, in spite of showing a similar torque at a lower angular velocity. Thus, the measurement of dynamic strength in this study was conducted at low and moderately high angular velocities (1.05 and 3.14 rad · s^{-1}, respectively).

For torque measurements, the participants were seated in an upright chair with arms folded over the chest and stabilized firmly at the shoulder, chest, hip, and mid-thigh via straps. The rotational axis of the dynamometer was visually aligned to the anatomical axis of the knee joint with the knee at a 1.57 rad of flexion, and the lower leg of the participant was attached to the lever arm of the dynamometer. The order of the leg examined and velocity set was randomized for each participant. After a standardized warm-up of 5 min of jogging and 5 min of stretching the leg muscles, participants were asked to take the prescribed position for torque measurements. The warm-up practice consisted of five submaximal repetitions of the task movements at each test speed to familiarize the participants with the test protocol. The standardized gravity correction procedure was performed before each trial. The participants performed maximal torque exertions in knee extension and flexion three times at 1.05 rad · s^{-1} and five times at 3.14 rad · s^{-1}, and rest periods of at least 2 min were allowed between trials. The reason for performing five repetitions at 3.14 rad · s^{-1} was that a few participants showed the highest torque on the fourth or fifth repetition in a preliminary experiment. The highest torque value was used for later analysis.

Data analyses

Limb dominance was reported by the participants based on the leg preferentially used for ball kicking, and confirmed by an experimenter observing the participants playing in official games. In the present study, dynamic strength was assessed as torque. Muscle volume is a major determinant of joint torque in humans (Fukunaga et al., 2001). Therefore, torque values at both test velocities were correlated to the product of the average value of the cross-sectional areas at the three slice levels and body height (CSA*ht, where CSA = cross-sectional area and ht = height). Since significant correlations [$r = 0.655$ ($P < 0.0001$) to 0.834 ($P < 0.0001$)] were observed between the two variables, the ratio of torque (T) to CSA*ht [T/(CSA*ht)] was calculated as an index to represent dynamic strength relative to muscle size.

Descriptive data are presented as means and standard deviations (s). A simple linear regression analysis was used to calculate the correlation coefficients between the measured variables. A two-way repeated-measures analysis of variance (ANOVA) with Scheffé's test was used to examine differences in cross-sectional area and torque between the dominant and non-dominant leg. Moreover, two-way ANOVA with Scheffé's test was used to examine differences in cross-sectional area and torque between the junior and senior players. If a significant interaction between age and thigh-slice level or test velocity was found, one-way ANOVA with Scheffé's test was used to identify the thigh-slice level or test velocity at which the difference between the two age groups lay. Statistical significance was set at $P < 0.05$.

Results

For all cross-sectional area and torque values, there were no significant effects of leg in junior ($F_{1,25} = 0.0001$ to 2.744, $P = 0.108$ to 0.991) or senior ($F_{1,19} = 0.539$ to 3.559, $P = 0.075$ to 0.415) players. In the following descriptions, therefore, only the effect of age on the measured variables was focused on.

In both the dominant and non-dominant leg, the total muscle compartment and quadriceps femoris were significantly greater in the senior than in the junior players ($F_{1,132} = 17.542$ to 47.115, $P < 0.0001$), with no significant interaction between age and thigh-slice level ($F_{2,132} = 0.902$ to 2.194, $P = 0.116$ to 0.408) (Table I). In contrast, the hamstrings and adductors showed significant interactions between age and thigh-slice level in both legs ($F_{2,132} = 3.929$ to 13.819, $P = 0.022$ to < 0.0001). One-way ANOVA indicated that the hamstrings at 30% ($P = 0.002$) and 50% of femur length ($P = 0.004$) and the adductors at 70% of femur length ($P < 0.0001$) in the dominant leg, and the hamstrings at 30% ($P < 0.0001$) and the adductors at 50% ($P = 0.011$) and 70% of femur length ($P < 0.0001$) in the non-dominant leg, were significantly greater in the senior than the junior players (Table I). In both legs, the hamstrings + adductors were significantly greater for the senior than for the junior players (dominant leg: $F_{1,132} = 44.557$, $P < 0.0001$; non-dominant leg: $F_{1,132} = 58.560$, $P < 0.0001$), with no significant interaction between age and the thigh-slice level (dominant leg: $F_{2,132} = 1.942$, $P = 0.147$; non-dominant leg: $F_{2,132} = 1.894$, $P = 0.155$).

In both legs, the differences between the two age groups in the percentage of each muscle group to total muscle compartment were small (Table II). In both legs, however, %QF was significantly greater in the junior than the senior players (dominant leg: $F_{1,132} = 9.319$, $P = 0.003$; non-dominant leg: $F_{1,132} = 11.735$, $P = 0.0008$), while %Ham + Add

Table I. Cross-section area (cm^2) in junior and senior players (mean ± *s*).

			Thigh slice levels			Two-way ANOVA	
Variable	Leg	Group	30% Fl	50% Fl	70% Fl	Scheffé test on group difference[a]	Interaction with thigh slice level
TMC	D	Junior	104.1 ± 11.7	148.3 ± 15.1	153.0 ± 16.4	J < S	n.s.
		Senior	112.7 ± 10.1	165.6 ± 14.1	171.6 ± 17.2		
	ND	Junior	106.2 ± 13.6	147.2 ± 14.3	149.6 ± 15.2	J < S	n.s.
		Senior	115.6 ± 9.1	165.8 ± 12.6	170.5 ± 16.2		
QF	D	Junior	57.7 ± 7.4	74.9 ± 7.7	69.3 ± 6.3	J < S	n.s.
		Senior	60.7 ± 5.9	81.7 ± 8.8	76.0 ± 8.0		
	ND	Junior	59.8 ± 5.9	74.1 ± 7.7	67.9 ± 6.3	J < S	n.s.
		Senior	62.7 ± 4.8	82.1 ± 7.4	75.7 ± 8.4		
Ham	D	Junior	37.5 ± 4.2	36.6 ± 4.4	15.4 ± 3.7	30%,50%Fl:J < S	$P = 0.0220$
		Senior	43.1 ± 5.0	40.8 ± 3.0	16.2 ± 4.4		
	ND	Junior	37.3 ± 4.6	36.0 ± 4.4	14.5 ± 3.3	30%Fl:J < S	$P = 0.0089$
		Senior	43.8 ± 4.3	40.0 ± 3.3	15.7 ± 4.1		
Add	D	Junior	1.8 ± 1.5	26.9 ± 5.4	58.2 ± 7.4	70%Fl:J < S	$P < 0.0001$
		Senior	1.3 ± 1.7	32.1 ± 6.8	68.4 ± 6.7		
	ND	Junior	1.8 ± 1.5	26.9 ± 4.4	57.3 ± 6.8	50,70%Fl:J < S	$P < 0.0001$
		Senior	1.6 ± 1.6	32.8 ± 6.5	68.2 ± 6.3		
Ham + Add	D	Junior	39.4 ± 4.4	63.4 ± 7.3	73.6 ± 9.5	J < S	n.s.
		Senior	44.5 ± 5.7	72.9 ± 7.2	84.6 ± 9.3		
	NDJ	Junior	39.1 ± 5.0	63.0 ± 7.2	71.8 ± 8.8	J < S	n.s.
		Senior	45.3 ± 5.0	72.8 ± 7.3	83.8 ± 8.5		

Note: Fl = femur length; TMC = total muscle compartment; QF = quadriceps femoris; Ham = hamstrings; Add = adductors; D = dominant; ND = non-dominant; J = junior; S = senior.

[a]Significant difference between mean values for junior and senior players ($P < 0.05$).

Table II. Percentage of each muscle cross-sectional area to total muscle compartment in junior and senior players (mean ± *s*).

			Thigh slice levels			Two-way ANOVA	
Variable	Leg	Group	30% Fl	50% Fl	70% Fl	Scheffé test on group difference[a]	Interaction with thigh slice level
%QF	D	Junior	55.4 ± 2.4	50.5 ± 2.1	45.3 ± 2.1	J > S	n.s.
		Senior	53.9 ± 2.9	49.3 ± 2.7	44.2 ± 2.1		
	ND	Junior	56.2 ± 2.3	50.4 ± 2.4	45.5 ± 2.1	J > S	n.s.
		Senior	54.3 ± 2.1	49.5 ± 2.5	44.4 ± 1.8		
%Ham	D	Junior	36.1 ± 2.4	24.7 ± 2.0	10.0 ± 2.0	n.s.	$P = 0.0107$
		Senior	38.3 ± 2.8	24.7 ± 1.9	9.4 ± 2.1		
	ND	Junior	35.2 ± 2.2	24.5 ± 1.5	9.6 ± 1.6	30%Fl:J < S	$P < 0.0001$
		Senior	37.9 ± 2.1	24.2 ± 1.7	9.1 ± 1.9		
%Add	D	Junior	1.7 ± 1.5	18.1 ± 2.6	38.0 ± 2.1	n.s.	$P = 0.0220$
		Senior	1.1 ± 1.4	19.3 ± 3.3	39.9 ± 2.2		
	ND	Junior	1.7 ± 1.3	18.3 ± 2.2	38.3 ± 2.2	n.s.	$P = 0.0457$
		Senior	1.3 ± 1.3	19.7 ± 3.3	40.0 ± 2.1		
%Ham + Add	D	Junior	37.9 ± 2.1	42.8 ± 1.8	48.0 ± 1.9	J < S	n.s.
		Senior	39.4 ± 3.1	44.1 ± 2.7	49.3 ± 2.2		
	ND	Junior	36.9 ± 2.0	42.8 ± 1.9	47.9 ± 1.9	J < S	n.s.
		Senior	39.2 ± 2.2	43.9 ± 2.5	49.2 ± 1.7		

Note: Fl = femur length; TMC = total muscle compartment; QF = quadriceps femoris; Ham = hamstrings; Add = adductors; D = dominant; ND = non-dominant; J = junior; S = senior.

[a]Significant difference between mean values for junior and senior players ($P < 0.05$).

was significantly greater in the senior than the junior players (dominant leg: $F_{1,132} = 12.562$, $P = 0.0005$; non-dominant leg: $F_{1,132} = 20.449$, $P < 0.0001$). The %Ham and %Add tended to be higher in the senior than in the junior players at 30% and 70% of femur length, respectively, and these showed significant interactions with age and thigh-slice level ($F_{2,132} = 3.160$ to 10.552, $P = 0.046$ to < 0.0001). One-way ANOVA indicated that only %Ham at 30% of femur length in the non-dominant leg was significantly higher ($P = 0.0005$) in the senior than the junior players.

The senior players showed significantly greater torque than the juniors in the two motions with both legs ($F_{1,88} = 24.907$ to 42.353, $P < 0.0001$), with no significant interaction with test velocity ($F_{1,88} = 0.105$ to 1.009, $P = 0.318$ to 0.764) (Table III). Moreover, the ratios of knee flexion to knee extension regarding torque for both legs were also significantly higher in the senior than in the junior players (dominant leg: $F_{1,88} = 7.992$, $P = 0.006$; non-dominant leg: $F_{1,88} = 6.262$, $P = 0.014$), with no significant interactions with test velocity (dominant leg: $F_{1,88} = 0.470$, $P = 0.495$; non-dominant leg: $F_{1,88} = 0.280$, $P = 0.598$), although the differences were small (Table IV). The significance of differences in torque between the junior and senior players remained when expressed as T/(CSA*ht) ($F_{1,88} = 4.121$ to 13.176, $P = 0.045$ to 0.0005) (Table V).

Discussion

Lateral dominance

In both the junior and senior players, no significant difference in muscle cross-sectional area or torque was observed between the dominant and non-dominant leg. An imbalance in the strength of soccer players related to lateral dominance has been studied extensively, but the findings are equivocal. In terms of concentric strength, a similarity between the dominant and non-dominant leg has been reported in junior (Rochcongar et al., 1988) and senior (Agre & Baxter, 1987; Rosene et al., 2001; Zakas, 2006) players, as observed here. However, others have reported an imbalance related to lateral dominance in the strength of either the knee flexors or extensors (Ergun et al., 2004; Gur et al., 1999; Magalhaes et al., 2004; McLean & Tumilty, 1993). In addition, in a study of junior soccer players, Kearns et al. (2001) reported that the thickness of the medial gastrocnemius was greater in the dominant than the non-dominant leg. The present results for junior players contradict this finding. In terms of cross-sectional area, however, our results are in line with those of Masuda et al. (2003), who examined the cross-sectional area of the quadriceps femoris, hamstrings, and adductors in university soccer players. The discrepancy between the results of Kearns et al. (2001) and those of the present study could be due to differences in the variables analysed and muscle groups examined. In addition, the fact that the participants were elite junior and senior soccer players would also suggest a lack of an imbalance in muscle cross-sectional area and torque between the dominant and non-dominant leg. Zakas (2006) did not identify any influence of lateral dominance in the knee extension and flexion strength of professional soccer players. Zakas noted that the training sessions and matches undertaken by professional soccer players appear to have resulted in a balance of strength between the left and right sides of the body, and that it is reasonable to assume that a high degree of skill in using both legs improves the ability to execute motor performances in soccer (Zakas, 2006). In addition, even at a young age, well-trained soccer players show no

Table III. Torque (N · m) in junior and senior players (mean ± *s*).

			Velocity		Two-way ANOVA	
Movement	Leg	Group	1.05 rad · s^{-1}	3.14 rad · s^{-1}	Scheffé test on group difference[a]	Interaction with test velocity
Knee extension	D	Junior	182.0 ± 28.4	137.7 ± 17.2	J < S	n.s.
		Senior	214.4 ± 31.7	161.1 ± 21.9		
	ND	Junior	179.0 ± 29.2	133.5 ± 19.3	J < S	n.s.
		Senior	211.3 ± 34.2	156.3 ± 20.0		
Knee flexion	D	Junior	96.2 ± 18.2	79.1 ± 15.5	J < S	n.s.
		Senior	122.7 ± 24.1	103.0 ± 19.6		
	ND	Junior	88.2 ± 20.4	79.5 ± 15.6	J < S	n.s.
		Senior	117.8 ± 20.7	101.2 ± 18.2		

Note: D = dominant; ND = non-dominant; J = junior; S = senior.
[a]Significant difference between mean values for junior and senior players ($P < 0.05$).

Table IV. Torque ratio of knee flexion to knee extension (mean ± *s*).

Leg	Group	Velocity		Two-way ANOVA	
		$1.05\ \mathrm{rad \cdot s^{-1}}$	$3.14\ \mathrm{rad \cdot s^{-1}}$	Scheffé test on group difference[a]	Interaction with test velocity
D	Junior	0.53 ± 0.07	0.58 ± 0.11	J < S	n.s.
	Senior	0.57 ± 0.06	0.64 ± 0.08		
ND	Junior	0.49 ± 0.07	0.60 ± 0.18	J < S	n.s.
	Senior	0.56 ± 0.08	0.65 ± 0.08		

Note: D = dominant; ND = non-dominant; J = junior; S = senior.
[a] Significant difference between mean values for junior and senior players ($P < 0.05$).

Table V. Torque ($\mathrm{kN \cdot m^{-2}}$) relative to the product of mean muscle cross-sectional area and height (mean ± *s*).

Movement	Leg	Group	Velocity		Two-way ANOVA	
			$1.05\ \mathrm{rad \cdot s^{-1}}$	$3.14\ \mathrm{rad \cdot s^{-1}}$	Scheffé test on group difference[a]	Interaction with test velocity
Knee extension	D	Junior	15.85 ± 2.12	11.89 ± 1.14	J < S	n.s.
		Senior	16.79 ± 2.12	12.59 ± 1.18		
	ND	Junior	15.54 ± 1.84	11.58 ± 0.99	J < S	n.s.
		Senior	16.32 ± 1.91	12.10 ± 1.06		
Knee flexion	D	Junior	18.81 ± 2.50	15.46 ± 2.43	J < S	n.s.
		Senior	20.82 ± 3.19	17.47 ± 2.44		
	ND	Junior	17.58 ± 3.50	15.92 ± 3.06	J < S	n.s.
		Senior	20.17 ± 2.79	17.34 ± 2.49		

Note: D = dominant; ND = non-dominant; J = junior; S = senior.
[a] Significant difference between mean values for junior and senior players ($P < 0.05$).

difference in force between the preferred and non-preferred leg (Shephard, 1999). Based on the above, it would appear that for the participants examined here, their own training programmes and/or soccer skills might have resulted in a balance in both muscularity and strength of the left and right sides of the body regardless of age.

Development of thigh muscularity

In both the dominant and non-dominant leg, cross-sectional area of the total muscle compartment, quadriceps femoris, and hamstrings + adductors were significantly higher in the senior than junior players, regardless of thigh-slice level. These differences might be explained in part by the fact that the senior players were significantly heavier than the junior players. However, significant differences in the hamstrings were only found at 30% and 50% of femur length, and at 50% and 70% of femur length for the adductors. Along the thigh, the cross-sectional area of the quadriceps femoris is maximal at about mid-thigh level (Akima et al., 2000). In contrast, the cross-sectional area of the hamstrings and adductors becomes greater at points proximal to the knee and hip joints, respectively. The present observations also indicated that the hamstrings and adductors were largest at 30% and 70% of femur length, respectively, on average. Thus, the differences in the hamstrings and adductors between the junior and senior players were significant at the slice level where the anatomical cross-sectional area of each muscle group becomes greater along the thigh.

Compared with the cross-sectional area of the quadriceps femoris at mid-thigh level in untrained, young adult Japanese men (74 $\mathrm{cm^2}$) (Kanehisa, Ikegawa, & Fukunaga, 1994) and boys aged 14–16 years (56 $\mathrm{cm^2}$) (Kanehisa, Ikegawa, Tsunoda, & Fukunaga, 1995), the corresponding values in the present study were about 17% and 34% greater for the junior and senior players, respectively. Although the cross-sectional areas of the hamstrings and adductors were not reported in these previous studies, when percentage of quadriceps femoris to total muscle compartment is calculated, one finds higher values in both the untrained young adult men (55%) and boys (56%) compared with the senior and junior soccer players (49–50%) in the present study. In addition, the %QF of an untrained population was reported to be almost constant after adolescence (Kanehisa et al., 1995). However, the %QF was slightly but significantly higher in the junior than the senior players regardless of the thigh-slice level in the present study, with the reverse being the case for %Ham + Add. Therefore, compared with untrained populations, the soccer players can be characterized by a predominant development of the hamstrings and/or adductors rather than of the quadriceps femoris, and a tendency towards hamstring and adductor development becomes more apparent through the continuation of soccer training from the junior to senior stage at a highly competitive level.

Implications of hamstring and adductor development

Why a significant difference existed in %QF and %Ham + Add between the two age groups remains unclear. However, it might be associated with the higher torque ratio of knee flexion to knee extension in the senior than in the junior players. Many studies have suggested that elite senior soccer players are likely to show higher knee flexion strength than younger or sub-elite players (Cometti et al., 2000; Gur et al., 1999; Oberg et al., 1986). Thus, the predominant development of the hamstrings and adductors in soccer players may be an advantage for attaining high-level soccer playing standards. In particular, such a predominant development would be beneficial for improving running speed. The hamstrings together with the adductor magnus and gluteus maximus are considered to make the most important contribution to maximal running speed (Delecluse, 1997). Previous reports of electromyograms recorded during sprinting have provided evidence that the hamstrings play a primary role in the propulsion phase (Mero, Komi, & Gregor, 1992). Also, Simonsen and colleagues (Simonsen, Thomsen, & Klausen, 1985) suggested that the adductor muscles of the thigh may be the most important movers of the flexor moment about the hip, which acts to balance the upper body during the powerful hip and knee joint extension in the ground phase of sprinting. We did not evaluate adductor strength (hip adduction) in the present study. A further study should be conducted to examine the possible association between sprinting ability and the muscularity and strength of the hamstrings and adductors in soccer players.

The hamstrings also contribute to stabilization of the knee joint in sprinting (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998; Osternig, Hamill, Lander, & Robertson, 1986), jumping, and ball kicking (Fried & Lloyd, 1992). During a powerful kick in soccer, the hamstrings are active in knee flexion in the backswing phase and in the downswing phase nearer to when the ball is struck (Wahrenberg, Lindbeck, & Ekholm, 1978). Hamstring activity in the latter phase causes a reduction in the rate of knee extension and acts to prevent hyperextension and possible damage to the knee (Robertson & Mosher, 1985). Thus, the greater development of the hamstrings compared with the quadriceps femoris may be assumed to be an advantage for not only achieving high-level performance but also for preventing injuries in senior players.

Torque relative to muscle size

As anticipated, the isokinetic torque was higher in the senior than in the junior players. The torque measured by the isokinetic dynamometer is a product of the applied force and the length of the lever arm of the dynamometer. In the present study, the seniors were significantly taller than the juniors, so it could be assumed that the senior players would have a longer lower leg length. Hence, the observed differences in torque might be simply attributable to the difference in lower leg length between the two groups. However, it should be noted that the senior players also showed higher values of T/(CSA*ht) than the juniors, regardless of the motion and test velocity.

As a possible explanation for this, we speculate that neuromuscular function relating to torque development in knee extension and flexion would differ between the two age groups. It has been suggested that a training programme involving a heavy-resistance, low-repetition system or ballistic movement can greatly improve neural activation during maximum voluntary contractions (Hoff, 2005; Sale, 1988; Wisloff et al., 2004). This can be an important factor in increasing muscle strength relative to muscle size (Sale, 1988). In addition, the key training stimuli for improving torque output on high-velocity contractions are repeated attempts to perform ballistic contractions and the high rate of force development of the ensuing contraction (Behm & Sale, 1993). The junior players examined in the present study had not been exposed periodically to systematic resistance exercises in their own training programmes. In contrast, the senior players had great experience of high-resistance and ballistic training as a part of their muscular fitness programmes. Considering that the ratio of knee strength to muscle size remains unchanged with age in untrained populations after late adolescence (Kanehisa et al., 1994, 1995), it might be assumed that the training background of senior players, rather than their age, is the reason why their T/(CSA*ht) values are higher than those of junior players.

Another possible reason for the age-related difference in T/(CSA*ht) is the influence of the percentages of the number and/or area of type II fibres on dynamic torque relative to muscle cross-sectional area. Ryushi and Fukunaga (1986) reported that isokinetic knee extension torque relative to the cross-sectional area of the quadriceps femoris was correlated with the percent number and percent area of type IIa fibres in the vastus lateralis muscle. Therefore, there is a possibility that, as a result of longer soccer training experience or selection processes, the proportions of the number and/or area of type IIa fibres may predominate in senior players, leading to a higher T/(CSA*ht) than in junior players.

In summary, the present study indicate that: (1) compared with junior players, senior players were characterized by a predominant development of the hamstrings and adductors and showed a higher dynamic torque relative to muscle size; and (2) neither junior nor senior players showed a significant influence of lateral dominance on the cross-sectional area of the thigh muscles or dynamic torque during knee extension and flexion.

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Stroke power consistency and 2000 m rowing performance in varsity rowers

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We studied the relationship between stroke power consistency and 2000 m rowing time besides determining maximal oxygen uptake (VO_{2max}) and leg extension power. The subjects ($n = 16$, male varsity rowers) carried out an incremental test to volitional exhaustion on a rowing ergometer, and the VO_2 at each stage was determined. The stroke power consistency was assessed by the coefficient of variation of power (CVP_{high}) at the highest workload at which each subject could maintain power. Besides the incremental test, 2000 m all-out rowing was performed on the ergometer and leg extension power was measured. Stepwise multiple regression analysis indicated that the 2000 m rowing time could be predicted by VO_{2max}, leg extension power and CVP_{high} in order of strength of standardized partial correlation coefficients as explanatory variables. The CVP_{high} correlated with the residual of the regression between 2000 m rowing time and VO_{2max}. The findings suggest that the stroke power consistency contributes to maintenance of the power during ergometer rowing.

Rowing involves repetitive cyclic motions with different directions repeated approximately 220–240 times during the 2000 m race. The time course of mean power and variations in motion and power during the stoke cycle have been documented (Hagerman et al., 1978; Mahler et al., 1984; Hartmann et al., 1993; Schabort et al., 1999). Henry et al. (1995) investigated strokes in tank rowing and found that power–oar angle curves for consecutive strokes and time course variations of the power and the oar angle represent skill parameters. Smith and Spinks (1995) determined in ergometer rowing work consistency and stroke-to-stroke consistency, in which similarities of force values were quantified after normalizing force data for each stroke with respect to time. The consistency evaluated by the coefficient of variation discriminated the ability level of the rowers. These findings indicate that the consistency in force, work and power of the stroke are determinants of performance. Also, the stroke power consistency correlates with the velocity of a rowing shell (Shimoda & Kawakami, 2004).

Physiological determinants including maximal oxygen uptake (VO_{2max}) and lactate and ventilatory thresholds of rowers have yielded large values (Secher, 1993; Shephard, 1998). Especially, an intimate relationship between rowing performance and VO_{2max} has been reported (Secher, 1993; Shephard, 1998; Cosgrove et al., 1999). Also, isokinetic and isometric knee extension strength measured in a simulated rowing position and leg extension power are correlated to ergometric rowing performance (Secher, 1975; Pyke et al., 1979; Yoshiga et al., 2000). These findings prompted us to suppose dependence of stroke power consistency, aerobic capacity, leg extension power and rowing performance.

Methods

Sixteen male university rowers volunteered to participate in this study [age 20.7 ± 0.9 years, height 176.2 ± 7.3 cm, body mass 72.5 ± 6.4 kg (mean ± SD)]. The subjects all had experience of 2000 m rowing competition from 1 to 3 years and trained regularly on a rowing ergometer (Concept II, Model C, Morrisville, Vermont, USA) and were at an average performance level of Japanese collegiate rowers. All procedures were undertaken with the informed consent of the subjects and the study was approved by the Ethics Committee of the Faculty of Sport Sciences, Waseda University, in the spirit of the Helsinki Declaration.

Experimental protocol

The subjects performed a continuous incremental test to volitional exhaustion on a rowing ergometer. After 1 min of rest sitting on the rowing ergometer, the subjects rowed at 150 W. The workload was increased by 50 W every second minute until exhaustion (Steinacker et al., 1986), while the subjects were encouraged. The subjects rowed at their preferable stroke rate and were instructed to keep exerting as constant as possible a power at each workload. The subjects monitored the power on the display of the ergometer. Expired air was sampled breath by breath and VO_2 was measured using an electronic spirometer (Aeromonitor AE-300S, Minato Medical Science Co., Ltd., Osaka, Japan). A 3-lead electrocardiogram (Cardiosuper 2E32, NEC Medical Systems, Tokyo, Japan) was monitored to measure the heart rate (HR). The VO_2, carbon dioxide expiration (VCO_2), ventilation (VE) and HR were averaged every 10th second and the power was also displayed.

A maximal bilateral leg extension power was determined by an isotonic dynamometer (Anaeropress 3500, Combi Co., Tokyo, Japan). The subjects sat and pressed their feet on the foot plate as intensively as possible in a horizontal direction until the legs were fully extended. The maximal leg extension power was the highest value obtained in five trials.

Before the incremental test on the rowing ergometer and the maximal leg extension power test, a 2000 m simulated rowing on the rowing ergometer was carried out to simulate the on-water race, starting with an initial spurt, followed by a constant pace at the preferable stroke rate and to perform their best. The total and split times were recorded.

VO_{2max}

VO_{2max} was defined when oxygen consumption reached a plateau and the respiratory exchange ratio (VCO_2/VO_2) was 1.1 or greater (Shephard, 1992). Maximal values of VCO_2, VE and HR were also determined. Calibration of the air flow of the expired air was carried out before each test using a calibration syringe. The spirometer was calibrated before and after each test with a certified gas mixture. Experiments were performed at a room temperature of 24 °C and at a humidity of 46%.

Stroke power consistency

The stroke power consistency at each workload was assessed by the coefficient of variance of power (CVP) (Smith & Spinks, 1995). The stroke power consistency for each subject was expressed as CVP at the highest workload at which the subject maintained power (CVP_{high}).

Statistics

Values are presented means ± SD, unless otherwise stated. Pearson's correlation coefficient (r) was used to examine the interrelationships between the variables. One-way analysis of variance (ANOVA) analyzed VO_{2max} and CVP at each workload during the test. To adjust for multiple comparisons when ANOVA showed a significant difference between groups, a Tukey *post hoc* test was used to identify which group differences accounted for the significant P value. Stepwise multiple regression analysis was conducted to select explanatory variables that could predict the 2000 m rowing time. The explanatory variables included the VO_{2max}, VO_{2max} per body mass and CVP_{high}. Single and multiple linear regression analyses were performed to predict 2000 m rowing time. The criterion of addition and elimination of variables was a P value <0.05 and more than 0.1, respectively. In each statistical analysis, the significance was accepted at the 0.05 level.

Results

The VO_{2max}, leg extension power and 2000 m rowing time were $4.1 \pm 0.4\,min^{-1}$, 2241 ± 286 W and 409.3 ± 12.2 s, respectively. All subjects maintained 300 W for 2 min and VO_{2max} was observed at the subsequent workload. Three subjects completed 350 W, and only one subject completed 2 min at 400 W. The CVP decreased from 3.0 ± 0.9 to 1.7 ± 0.5% (Fig. 1).

The 2000 m rowing time correlated with VO_{2max} ($r = -0.61$, $P = 0.012$), leg extension power ($r = -0.68$, $P = 0.004$) and with CVP_{high} ($r = 0.69$, $P = 0.003$). Stepwise multiple regression analysis indicated that the 2000 m rowing time could be predicted by the VO_{2max}, leg extension power and CVP_{high} (adjusted coefficient determination $r^2 = 0.79$) in this order of strength of standardized partial correlation coefficients (Table 1). The CVP_{high} correlated with the residual of the single regression between 2000 m rowing time and VO_{2max} ($r = 0.64$, $P = 0.007$) but did not correlate with those between 2000 m rowing time and leg extension power (Fig. 2).

Discussion

The major finding of study is that the 2000 m rowing time correlated with VO_{2max}, leg extension power and CVP_{high}. The CVP_{high} correlated with the residual of the single regression model of the 2000 m rowing time and VO_{2max}. Although the correlation between rowing performance and VO_{2max} of rowers is widely recognized (Secher, 1983; Kramer et al., 1994; Cosgrove et al., 1999), rowers with similar

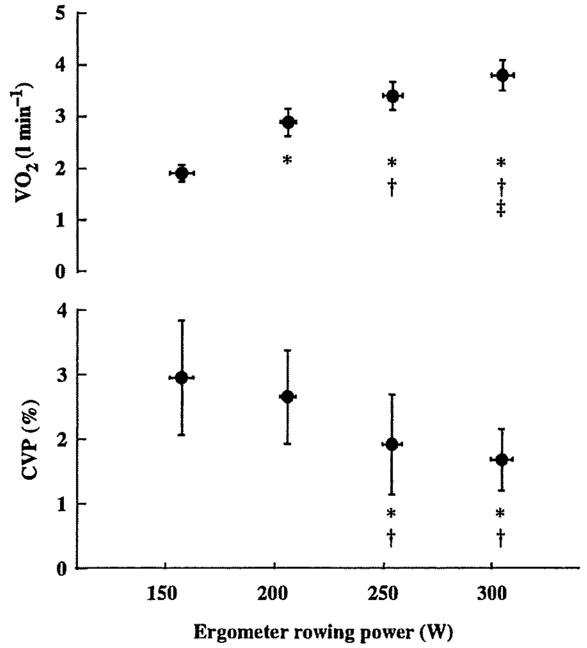

Fig. 1. Power and physiological parameters at different ergometer rowing workloads. *Different from 150 W; †different from 200 W; ‡different from 250 W. VO_{2max}, maximal oxygen uptake; CVP, coefficient of variance of power. Values are means ± SD.

Table 1. Multiple regression between 2000 m rowing time and the selected variables ($n = 16$)

Criterion variable	Explanatory variable	Regression coefficient	Standard error	Partial correlation coefficient	P value
2000 m rowing time (s)	VO_{2max} ($L\,min^{-1}$)	−13.0	3.57	−0.47	0.003
	Leg extension power (W)	−0.02	0.006	−0.45	0.004
	CVP_{high} (%)	11.3	4.54	0.34	0.029

VO_{2max}, maximal oxygen uptake; CVP, coefficient of variance of power.

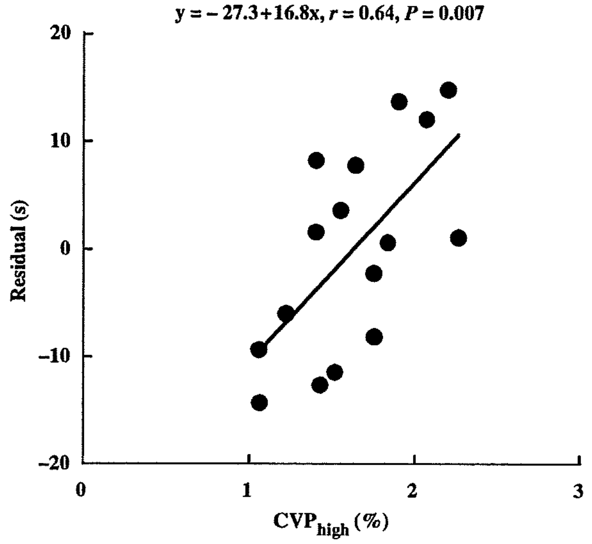

Fig. 2. Relationship between the residual of the single regression between 2000 m rowing time and maximal oxygen uptake, and coefficient of variation of power (CVP) at the highest workload.

VO_{2max} have different rowing performance (Steinacker et al., 1986; Schwanitz, 1991). The correlation between CVP_{high} and the residual of the single regression between 2000 m rowing time and VO_{2max} suggests that the stroke power consistency is related to factors influencing rowing performance that cannot be explained by VO_{2max}. Ergometer rowing performance reflects the rotational motion of flywheel affected by air resistance. When the stroke power is consistent, the flywheel continues to rotate steadily and this would be advantageous for efficient conversion of physiologic to mechanic power. Dal Monte and Komor (1989) indicate that the force during rowing is affected by oscillation of peak force during the drive portion of the stroke cycle. Although rowing power is influenced by the VO_{2max} of the rowers, the force transmitted to an ergometer is also influenced by the stroke power consistency.

There was no significant relationship between CVP_{high} and leg extension power. Competitive rowing is characterized by sustained high forces (Hartmann et al., 1993). However, there is no relationship between leg extension power and the endurance characteristics of force and power in rowing. It appears from the present result that the stroke power consistency is not strongly related to the single effort.

Rowing performance correlates with the absolute but not with the relative VO_{2max} ($VO_{2max}\,kg^{-1}$ body weight) of rowers (Secher, 1993; Steinacker, 1993; Shephard, 1998; Yoshiga et al., 2000) as confirmed in this study. We further found that there was a negative correlation between the CVP_{high} and VO_{2max} per body mass ($r = -0.64$, $P = 0.008$). Higher CVPs at lower workloads (150 and 200 W) reflect the difficulty of maintaining a high power. But low-intensity CVPs were not related to rowing performance or aerobic capacity. No significant difference in CVPs between at 250 and 300 W suggests that the CVP reaches a level that is inherent to each subject, which could be an index of rowing performance other than the endurance capacity and leg extension power.

Perspectives

The present findings suggest that rowing performance can be evaluated by VO_{2max}, leg extension power and stroke power consistency. The stroke power consistency is related to the factors influencing rowing performance that cannot be explained by VO_{2max} alone. Although we studied the stroke power consistency in ergometric rowing, we would expect that the stroke power consistency plays a more important role in on-water rowing, where manipulation of oars and maintenance of boat balance under variable environmental conditions are required.

Key words: aerobic capacity, leg extension power, ergometric rowing.

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Differences among lower leg muscles in long-term activity during ambulatory condition without any moderate to high intensity exercise

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Abstract

The present study aimed to investigate differences among the soleus (Sol), medial gastrocnemius (MG) and tibialis anterior (TA) in electromyogram (EMG) activities during ambulatory condition without any moderate to high intensity exercise. From 10:00 to 17:00, seven healthy graduate students participated in EMG recordings, which included the measurements during maximal voluntary efforts. During the long-term EMG recoding, the subjects were instructed to perform normal daily routines, including desk work and the attendance of lectures. EMG signals from the three muscles were averaged every 0.1 s and expressed as a percentage (%MVE) of those obtained with maximal voluntary efforts, averaged over 1 s. An EMG burst which had an amplitude >2%MVE and a duration >0.1 s was defined as muscular activity. Regardless of muscles examined, the amplitude of the greater part of all bursts observed over the recording time was less than 30%MVE. The summed duration of all bursts over the recording time was significantly greater in Sol than in MG and TA, without a significant difference in the summed number of all bursts among the three muscles. The percentage of the summed duration of bursts at less than 10%MVE to that over the recording time was significantly higher in Sol and TA than in MG, but the corresponding value at $20 \leqq \%\text{MVE} < 30$ was lower. Thus, EMG responses during ambulatory condition without any moderate to high intensity exercise differed among the three muscles, even between synergists: Sol was predominantly activated with low burst amplitudes as compared to MG.

Keywords: Electromyogram; Plantarflexors; Dorsiflexors; Freely moving; Muscle-related difference

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1. Introduction

In freely moving ambulatory individuals, major changes in physical activity involve movement of the lower limb (Anastasiades and Johnston, 1990). Therefore, recording the habitual activity patterns of major skeletal muscles located in the lower limbs can be a valuable approach to monitoring muscle activities that are more directly related to spontaneous physical movements and their variations during daily living.

Recent technological advances have increased the number of studies using long-term electromyogram (EMG) recordings in caged animals performing daily activities (Hodgson et al., 2001). For human muscles, too, this technique has been used to quantify tremors or spasticity in individuals with Parkinson's disease or spinal cord injuries (Scholz et al., 1988; Tepavac et al., 1992). Recently, Mork

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and Westgaard (2005, 2006) have tried to quantify the habitual activity patterns of upper trapezius and low back muscles of healthy individuals at different levels of intensity and presented a substantial amount of data on the repeatability of long-term EMG recordings. For normal ambulatory individuals, however, only two studies have applied this technique to lower limb muscles (Kern et al., 2001; Monster et al., 1978). Among the limited findings available, Kern et al. (2001) reported that, as a result of analysis for EMG bursts exceeding 2% of those during maximal voluntary efforts, the mean amplitude in a 10-h recording is greater in leg muscles than in hand and arm muscles.

Among muscles located in the lower limb, it is known that there are marked differences between plantarflexors and dorsiflexors in twitch responses and susceptibility to fatigue (Belanger et al., 1983). Similarly, although the gastrocnemius and soleus muscles are synergistic muscles as plantarflexors, they differ considerably in physiological cross sectional area (Fukunaga et al., 1992), muscle fiber composition (Johnson et al., 1973), muscle architecture (Kawakami et al., 1998) and contractile properties (Vandervoort and McComas, 1983). These points tempt us to assume that, even in ambulant conditions without any moderate to high intensity exercise, the intensity and/or duration of activities will differ between opposing and/or synergistic muscles. In relation to this assumption, Monster et al. (1978) have shown that, as a result of an 8-h EMG recording with a burst detection threshold set at 8% of maximum, the percentage of total active time over the recording time and average active time per contraction were longer in the soleus muscle than in the gastrocnemius muscle. In any case, with regard to the existence of differences among lower limb muscles in EMG responses during non-restrained daily living, less information is available from previous studies. Notably, it is unknown how the number and/or duration of EMG bursts at a given intensity differs among the lower limb muscles as habitual activity patterns under ambulant conditions.

By using long-term EMG recording technique, therefore, the present study tried to investigate the difference in the activities of lower leg muscles, i.e., the gastrocnemius, soleus and tibialis anterior muscles during ambulant condition without any moderate to high intensity exercise. To this end, we quantified the level and duration of the activity of the three muscles in the daily routines of graduate male students, which was mainly consisted of desk work and the attendance of lectures.

2. Methods

2.1. Subjects

Seven healthy young males voluntary participated in this study. The means (±standard deviation, SD) of age, height, and body mass in the subjects were 24.3 (±1.6) yr, 172.7 (±5.0) cm, and 70.0 (±4.2) kg, respectively. All subjects were graduate students and had no known history of peripheral nerve dysfuncfion or other types of neurological disorders. They were either sedentary or mildly active, but none was currently involved in any type of exercise program exceeding 30 min/day and 2 days/week. This study was approved by the National Space Development Agency of Japan and was consistent with their requirement for human experimentation. Each subject was informed of the procedures and purpose of the study, and gave their written informed consent.

2.2. Experimental design

EMGs were recorded from the medial gastrocnemius (MG), soleus (Sol), and tibialis anterior (TA) muscles using a portable EMG device (ME3000P8, Mega Electronics, Finland). Subjects came to the laboratory at 9:00. The EMG recording started at 10:00 and ended at 17:00. Prior to the long-term EMG recordings, the subjects performed isometric contractions with maximal voluntary effort in two movement tasks, i.e., plantarflexion and dorsiflexion. After the completion of the maximal isometric contractions, the subjects left the laboratory. They were instructed to perform normal daily routines, including desk work and the attendance of lectures, without any moderate to high intensity exercise. The subjects came back to the laboratory at 17:00. Each subject performed the experimental procedure two times with an interval of one week to confirm the day-to-day difference of long-term EMG recordings. The first and second sessions were referred to as DAY1 and DAY2, respectively. The EMG recording time not including the EMG measurements during maximal isometric contractions did not significantly differ between DAY1 and DAY2, and averaged 6.5 h a session.

2.3. Measurements

2.3.1. EMG recordings

After careful abrasion of the skin, pairs of disposable surface electrodes (Blue Sensor, Medicotest, Denmark) were placed over the belly of each of the muscles examined on the right leg (20 mm apart between the electrodes). The positions of electrodes were marked with ink to make sure they were the same on both DAY1 and DAY2. To stabilize their location during the recording period including EMG measurements during maximal isometric contractions, the electrodes were fixed with surgical tape and covered with barrel-shaped mesh supporters. The electrodes were connected to a portable EMG device which was protected in a soft case and worn around the subject's waist during the measurements. The EMG signals were amplified (×412), filtered (bandwidth 8–500 Hz), sampled at 1000 Hz, full-wave rectified and averaged over 0.1 s. These data were stored on a PCMCIA card for subsequent analysis. The procedure for long-lasting EMG recordings in different days has been already established in our recent study (Kouzaki et al., 2007).

2.3.2. EMG measurements during maximal isometric contractions

The subjects performed maximal isometric contractions of the plantarflexion and dorsiflexion using a dynamometer (VTF-002R/L, Vine, Japan) designed especially for the determination of ankle joint torques. During the maximal isometric contractions, the EMGs from MG, Sol, and TA were recorded under the conditions mentioned above. For each of the two tasks, the subjects sat in an adjustable chair with support for the back and hips with the hip joint flexed 1.57 rad. During the measurements, the back and hips were held tightly to the seat with adjustable lap belts. The rotational axis of the ankle joint was aligned with that of the lever arm of the dynamometer. In the plantarflexion and dorsiflexion, the subject's right ankle was set at 1.57 rad (anatomical position) with the knee joint fully extended and the foot was securely strapped to a foot plate connected to the lever arm of the dynamometer.

After a warm-up procedure with submaximal contractions, the subject performed maximal isometric contractions for each of the two movements. The order of the execution of the two conditions was randomized for each subject. Each of the two movement tasks was repeated at least two times per subject with an interval of 1 min between trials and at least 5 min between the tasks. In each trial, the subjects were required to maintain the maximal isometric contraction for about three seconds. Torque signals were A/D converted at a sampling rate of 100 Hz (PowerLab16SP, AD instrument, Australia) and analyzed by a personal computer (DELL Dimension XPS). The trial in which the highest peak torque was observed was used for the subsequent analysis of EMG during the maximal isometric contractions. The EMGs as well as torque during the maximal isometric contractions were averaged over one second around a data point where the torque peaked. The average EMG value was referred to as MVE and used to normalize EMG activities during long-lasting recording.

2.3.3. *Physical activity*

Steps and exercise energy expenditure during the long-term EMG recording were measured using a pedometer (Lifecoder, Suzuken, Japan) with a built-in accelerator which counts the acceleration of vertical direction during physical movements (Harada et al., 2001).

2.3.4. *Data analysis*

After completion of the EMG measurements, the stored data were transferred to a personal computer. Fig. 1 indicates a typical example of a long-term EMG recording in one subject. All data except for those recoded in MVE measurements (about 30 min) were analyzed as long-term EMG data. For the data analysis, an original program written by Real Basic (Real Software) was used. EMG bursts which had an amplitude >2% of MVE and a duration >0.1 s were defined as muscular activity (Kern et al., 2001). In each EMG burst, two outcome variables were determined as described by Kern et al. (2001): (1) burst duration, an interval that had an amplitude >2% of MVE, and (2) burst amplitude, mean value of burst amplitude expressed as a percentage of MVE (%MVE). As total indexes representing EMG data over the recording time, two outcome variables were quantified: (1) the summed number of all bursts (TI-SNB) and (2) the summed duration of all bursts (TI-SDB). Furthermore, each EMG burst was stratified into ten levels in accordance with the %MVE; the first level was 2 < %MVE < 10 and the remainders were 10≦, 20≦, 30≦, 40≦, 50≦, 60≦, 70≦, 80≦, and 90 ≦ %MVE. Within each of the ten stratified levels, the summed number (SI-SNB) and duration (SI-SDB) of bursts were quantified as stratified indexes. In addition to the absolute values, SI-SNB and SI-SDB were expressed as a percentage of TI-SNB and TI-SDB, respectively, and referred to as %SI-SNB and %SI-SDB, respectively.

2.3.5. *Statistics*

Descriptive data were presented as means ± SDs. A Wilcoxon test was used to test the difference between DAY1 and DAY2 in the variables concerning the physical activity, torque and MVE during the maximal isometric contraction, and the total indexes of long-term EMG. The corresponding difference in stratified indexes at each of the ten stratified levels was also examined by Wilcoxon test. Nonparametric one-factor, repeated measures analysis of variance (Kruskal–Walllis) with a post hoc comparison (Steel–Dwass test) was used to compare the total indexes and the stratified indexes at each of the stratified levels of long-term EMG among the three muscles. The probability level for statistical significance was set at $P < 0.05$.

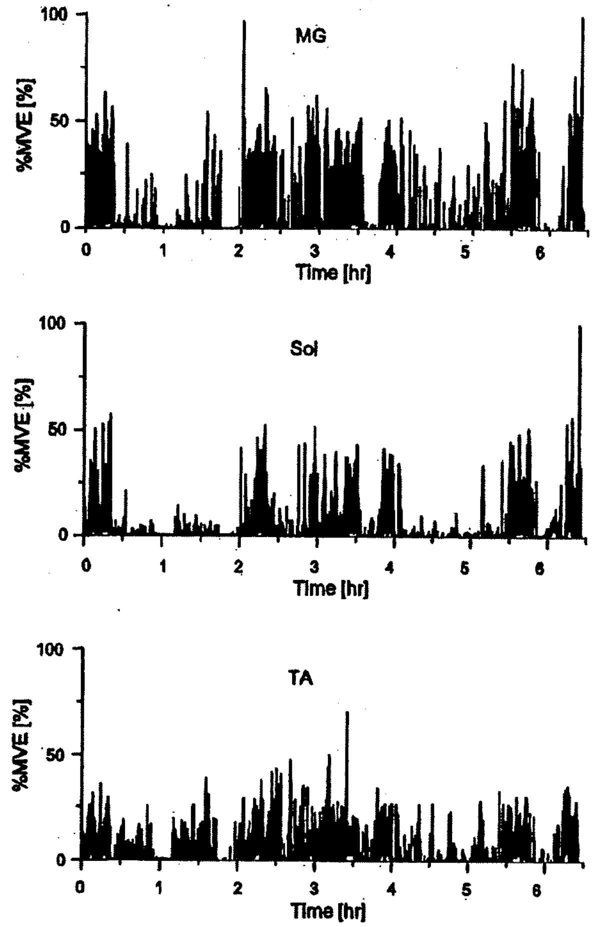

Fig. 1. An example of EMG recordings not including MVE measurements of the three muscles in one subject. The signals were averaged every 0.1 s and expressed as a percentage (%MVE) to those obtained for maximal voluntary contractions, averaged over 1 s.

3. Results

3.1. *DAY1 versus DAY2*

Table 1 summarizes the descriptive data on physical activity, the torque and MVE determined on DAY1 and DAY2. There were no significant differences ($P = 0.208$–0.575) between DAY1 and DAY2 in any of the variables listed in Table 1.

On both DAY1 and DAY2, there were large inter-individual variations in TI-SNB (736–6485 bursts for MG, 765–6472 bursts for Sol, and 785–5418 bursts for TA) and

Table 1
Descriptive data on physical activity, and averaged EMG (MVE) and torque during maximal isometric contractions in the separated 2 days

Variables	DAY1	DAY2
Physical activity		
Steps, *n*	4561.5 ± 2997.4	4783.6 ± 2858.6
Exercise energy expenditure, kcal	152.3 ± 102.9	158.3 ± 98.3
Torque, Nm		
Plantarflexion	194.6 ± 36.0	193.6 ± 38.5
Dorsiflexion	33.8 ± 15.5	30.6 ± 12.9
MVE, μV		
MG	328.6 ± 125.5	318.5 ± 87.1
Sol	284.3 ± 102.7	303.5 ± 86.2
TA	394.7 ± 71.6	420.5 ± 74.2

Values are means ± SDs.

TI-SDB (2290.3–10515.8 s for MG, 2916.5–11950.3 s for Sol, and 1513.4–8014.9 s for TA). For each muscle, however, there were no significant differences between DAY1 and DAY2 in TI-SNB ($P = 0.237–0.735$) and TI-SDB ($P = 0.128–0.735$). As shown in Fig. 1, there were EMG activities exceeding 80%MVE. In relation to the duration of the burst defined as muscular activity, however, there was no burst beyond 80%MVE in all three muscles. The differences between DAY1 and DAY2 in SI-SNB and SI-SDB were also not significant in any of the muscles; $P = 0.128–>0.999$ for SI-SNB and $P = 0.128–>0.999$ for SI-SDB. These results indicated that the intra-individual response in the repeated long-term EMG recordings was relatively invariant in spite of large inter-individual variations in the EMG responses. Therefore, data obtained from the 2 days were pooled for all subsequent analyses concerning the muscle-related differences in the long-term EMG responses.

3.2. Muscle-related differences

There was no significant difference in TI-SNB among the three muscles: 2819.7 (±1652.5) bursts for MG, 3262.0 (±1517.7) bursts for Sol and 2968.2 (±1250.0) bursts for TA (Fig. 2). On the other hand, TI-SDB was significantly greater in Sol (7076.1 ± 2911.6 s) than in MG (4450.2 ± 2337.7 s) and TA (4000.0 ± 1805.4 s). The percentage of TI-SDB to the recording time was 30.4 (±12.0)% for Sol, 19.1 (±9.8)% for MG and 17.2 (±7.6)% for TA.

The amplitude of most of the bursts obtained here were less than 30%MVE. The percentage of the summed number of all bursts at less than 30%MVE to TI-SNB was 97.8 (±2.7)% for MG, 99.2 (±1.1)% for Sol, and 99.5 (±1.2)% for TA. There was no significant difference among the three muscles ($P = 0.760$) in the summed number of all bursts at less than 30%MVE: 27733.5 (±1455.7) for MG, 3243.5 (±1521.2) for Sol, and 2961.8 (±1254.7) for TA. And so, the examinations on muscle-related difference in the stratified indexes were performed using EMG data of which the amplitude was less than 30%MVE.

Table 2 indicates the mean and SD values of SI-SNB and %SI-SNB at less than 30%MVE, respectively, in each of the three muscles. There was a tendency that Sol and TA showed more EMG bursts than MG at less than 10%MVE (Table 2) and vice versa at 20 ≦ %MVE < 30. Both SI-SNB and %SI-SNB at 20 ≦ %MVE < 30 were significantly greater in MG and Sol than in TA.

At less than 10%MVE, Sol showed significantly greater SI-SDB than MG and TA (Table 3). At 20 ≦ %MVE < 30, SI-SDB was significantly greater for MG and Sol than for

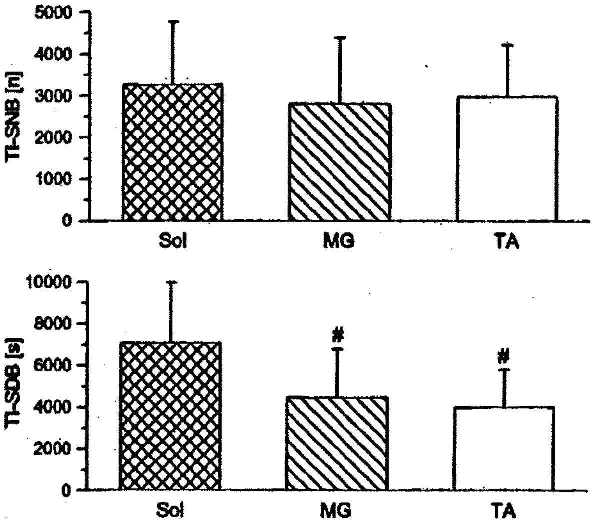

Fig. 2. Comparison among the three muscles of the summed number of all bursts (TI-SNB) and the summed duration of all bursts (TI-SDB) over the recording time. Values are means ± SDs. # denotes that TI-SDB values for MG and TA were significantly ($P < 0.05$) lower than that for Sol.

Table 2
Descriptive data on the summed number of bursts (SI-SNB) and its percentage (%SI-SNB) to TI-SNB in each of the stratified levels less than 30%MVE

Variables	Levels	Muscles			Steel–Dwass test*
		MG	Sol	TA	
SI-SNB, *n*	2 < %MVE < 10	1659.6 ± 659.1	2064.3 ± 775.5	2238.5 ± 991.1	
	10 ≦ %MVE < 20	736.1 ± 589.5	985.8 ± 1000.7	688.4 ± 562.7	
	20 ≦ %MVE < 30	337.9 ± 516.5	193.4 ± 243.7	34.9 ± 30.8	MG, SoL > TA
%SI-SNB, %	2 < %MVE < 10	65.5 ± 17.3	68.0 ± 16.7	75.1 ± 13.7	
	10 ≦ %MVE < 20	23.8 ± 11.0	25.7 ± 13.9	22.7 ± 11.3	
	20 ≦ %MVE < 30	8.5 ± 8.7	5.5 ± 5.8	1.7 ± 2.8	MG, Sol > TA

Values are means ± SDs.
* $P < 0.05$.

Table 3
Descriptive data on the summed duration of bursts (SI-SDB) and its percentage (%SI-SDB) to TI-SDB in each of the stratified levels less than 30% MVE

Variables	Levels	Muscles			Steel–Dwass test*
		MG	Sol	TA	
SI-SDB, s	2 < %MVE < 10	1332.8 ± 526.8	3766.6 ± 1809.6	2046.8 ± 943.1	Sol > MG, TA
	10 ≦ %MVE < 20	1539.0 ± 1063.9	2401.4 ± 1405.1	1580.1 ± 1037.5	
	20 ≦ %MVE < 30	928.7 ± 831.9	668.7 ± 430.7	224.59 ± 426.0	MG, Sol > TA
%SI-SDB, %	2 < %MVE < 10	33.8 ± 14.6	52.4 ± 14.1	53.7 ± 19.4	SoL, TA > MG
	10 ≦ %MVE < 20	32.9 ± 13.4	32.7 ± 11.2	36.9 ± 11.6	
	20 ≦ %MVE < 30	18.5 ± 10.5	9.5 ± 5.6	4.9 ± 7.9	MG > Sol > TA

Values are means ± SDs.
* $P < 0.05$.

TA. The %SI-SDB at less than 10%MVE was significantly higher in Sol and TA than in MG. However, the corresponding value at 20 ≦ %MVE < 30 was higher in MG than in Sol and TA and in Sol than in TA (Table 3).

4. Discussion

The main purpose of the present study was to examine the differences among the three muscles located in the lower leg in the spontaneous activities without any moderate to high intensity exercise. One of the present findings was that Sol had significantly higher value than MG and TA for TI-SDB, despite that TI-SNB was similar among the three muscles. This indicates that Sol is activated more continuously than MG and TA. As described earlier, a prior study has shown that, for human muscle, the duration of total activity during normal daily use can be related to the proportion of type I fibers (Monster et al., 1978). Hensbergen and Kernell (1997), who examined daily spontaneous activities in the ankle muscles of cats, have suggested that differences in the total duration of activity largely reflect differences in the extent to which the various muscles and muscle regions are used for long-lasting stabilizing contractions, which may be related to fiber-type composition. However, Kern et al. (2001) challenged the findings mentioned above on analyzing the daily activities of the human first dorsal interosseus, biceps brachii, vastus medialis, and vastus lateralis. We cannot explain the discrepancies between the findings of the two human studies. From the finding of an autopsy study (Johnson et al., 1973), however, the mean percentage of type I fibers is high for Sol (86% at surface and 89% at depth) than for MG (51%) and TA (73% at surface and depth). When the discussion is limited to the three muscles, therefore, the observed difference in TI-SDB between Sol and the other two muscles support the finding of Monster et al. (1978).

Regardless of muscles, the amplitude of the greater part of all bursts was less than 30%MVE. Especially, the bursts at less than 10%MVE accounted for 66–75% of the summed number of bursts over the recording period (Table 2). Sawai et al. (2004) reported that the integrated EMG per time of lower limb muscles for young adults in various daily actions such as postural maintenance and body transfer actions was less than 20–30% of the maximum voluntary contraction. Thus, it is reasonable to assume that the present result concerning the burst amplitude can be largely attributed to the fact that the long-term EMG recording was performed during the daily routines of graduate students, which were mainly consisted of desk work and the attendance of lectures. Again, Jonsson (1978, 1982, 1988), who examined the amplitude probability distribution function (APDF) in long-lasting works, indicated that the amplitude probability level reaches around 1.0 at 15–30% of maximum voluntary contraction in works which the worker can complete without discomfort. Therefore, the present result that the amplitude of greater part of all bursts was less than 30%MVE may be also considered to be a pattern of EMG bursts during long-lasting ambulatory condition with less muscular fatigue.

Among the three muscles examined, MG and Sol have a functional linkage as synergists of plantarflexors. In addition to TI-SDB, however, significant differences between the two muscles were found in SI-SDB and %SI-SDB, too, in spite of no significant differences of SI-SNB and %SI-SNB at each level. Namely, the SI-SDB and %SI-SDB at less than 10%MVE was significantly higher in Sol than in MG. On the other hand, %SI-SDB at 20 ≦ %MVE < 30 for Sol was significantly lower than that for MG. Thus, Sol compared to MG was predominantly activated with lower burst amplitudes and MG compared to Sol with higher burst amplitudes.

In freely moving cats, the profiles of forces produced by MG and Sol during the full range of hindlimb movements in posture, locomotion, and jumping appear to be precisely matched to the different characteristics of the motor-unit populations composing these synergistic muscles (Walmsley et al., 1978). In human experiments, it has been shown that there are differences between MG and Sol in EMG activities during quiet standing (Masani et al., 2003), calf raising (Kinugasa and Akima, 2005), and walking (Gottschall and Kram, 2003). Masani et al. (2003) provided evidence that, compared to Sol, the pattern of EMG activities for MG during quiet standing was more phasic. Borg et al. (2007) suggested that MG is to a large extent responsible for the phasic control of the anterior–posterior balance during quiet standing. In addition, MG compared to Sol showed a greater increment in EMG activity during calf raising (Kinugasa and Akima, 2005) and walking (Gottschall and

Kram, 2003) with increasing exercise intensity. In the present result, the SI-SDB at less than 10%MVE was grater in Sol than MG, but the corresponding difference in that at $20 \leqq$ %MVE < 30 was not significant. Taking this into account together with the previous findings cited above, it might be assumed that, in accordance with the different characteristics of the motor-unit populations, the activities of MG would be added to those of Sol in physical actions which require increasing force output of plantarflexors.

The SI-SNB and SI-SDB at $20 \leqq$ %MVE < 30 for TA were significantly lower than those for MG and Sol. In addition, SI-SDB at less than 10%MVE was also significantly lower in TA than in Sol, in spite of similar values of SI-SNB and %SI-SNB at the corresponding level. Thus, the present results indicate that TA is predominantly activated with low burst amplitudes as compared to MG and Sol, with shorter duration than Sol. Borg et al. (2007), who analyzed EMG activity and sway data from quiet and perturbed standing, reported that TA EMG was generally quiet except in the beginning of the perturbation trials when the perturbation mass was on the participant while the dorsal flexors resisted the tug. This is because in standing posture the ankle extension torque is continuously required since the center of mass of the body is located in front of the ankle joint (Smith, 1957). Consequently, even if the percentage of type I fibers for TA is more comparable to that for Sol rather than MG (Johnson et al., 1973), TA will not be activated as frequently as Sol to stabilize body posture during quiet standing.

TA is likely the most representative muscle for preparatory adjustment in sit-to-stand movement (Goulart and Valls-Sole, 1999), which might be assumed to be a major action performed by the subjects examined here. From the findings of Goulart and Valls-Sole (1999), however, the activity of TA was greatly diminished after take-off from seat, although TA was the muscle activated first. Conversely, Sol was the last muscle activated, but it remained active during standing. On the other hand, Ericson et al. (1986) reported that TA was activated during the entire walking cycle with greater amplitude of bursts at the time of heel strike and at the beginning of acceleration in the swing phase, in which MG and Sol were less activated. In their results, however, the peak activity of TA was lower than those of MG and Sol. In addition, Gottschall and Kram (2003) showed that TA did not change its activation level during horizontal walking regardless of aiding and impeding forces. In their study, the averaged EMG for MG decreased by 41% and increased by 65% with adding and impeding forces, respectively, corresponding to 10% of body weight. Again, Chiu and Wang (2007) indicated that increased walking speed caused a significant increase in the activity of MG, but did not in that of TA. These points partially explain the observed differences in the stratified indexes between TA and either MG or Sol.

Before summarizing the present results, we should comment the limitations of the present study, in relation to the experimental design taken. First, we have no data concerning not only the muscle fiber composition of the subjects examined but also their kinetic and kinematic profiles during the EMG recordings. And so, we cannot clear the physiological reasons for the observed differences in EMG responses among the three muscles. Second, the present study examined relatively small number of subjects. In addition, the graduate students were selected as the subjects and their daily routines, which were mainly consisted of desk work and the attendance of lectures, were subjected for collecting EMG data. Hence, the findings obtained here may be considered as a quantitative result of long-term EMG activities during sedentary living. However, there is a possibility that the results on the total and stratified indexes might differ from those obtained here when the EMG data are determined under different ambulatory conditions, or when different populations are selected as subjects. Further study needs to clear whether the muscle-related differences observed in the total and stratified indexes can be generalized as the profile of long-term EMG activities in freely moving ambulatory individuals, regardless of the subjects mentioned above.

In summary, the results of the present study indicated that EMG responses in the daily routine of graduate students among the three muscle groups located in the lower leg: (1) regardless of muscles, the amplitude of greater part of all bursts was less than 30% of maximal voluntary efforts, (2) although there were no significant differences in the summed number of all EMG bursts over the recording time among Sol, MG, and TA, the summed duration of all bursts was greater in Sol than in MG and TA, and (3) Sol and TA are predominantly activated with low burst amplitudes as compared to MG.

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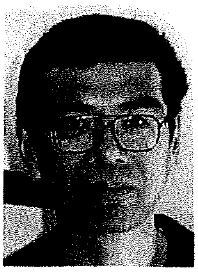

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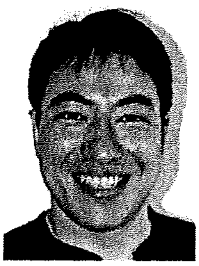

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Effects of knee joint angle on the fascicle behavior of the gastrocnemius muscle during eccentric plantar flexions

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Abstract

The present study aimed to clarify the effects of knee joint angle on the behavior of the medial gastrocnemius muscle (MG) fascicles during eccentric plantar flexions. Eight male subjects performed maximal eccentric plantar flexions at two knee positions [fully extended (K0) and 90° flexed (K90)]. The eccentric actions were preceded by static plantar flexion at a 30° plantar flexed position and then the ankle joint was forcibly dorsiflexed to 15° of dorsiflexion with an isokinetic dynamometer at 30°/s and 150°/s. Tendon force was calculated by dividing the plantar flexion torque by the estimated moment arm of the Achilles tendon. The MG fascicle length was determined with ultrasonography. The tendon forces during eccentric plantar flexions were influenced by the knee joint angle, but not by the angular velocity. The MG fascicle lengths were elongated as the ankle was dorsiflexed in K0, but in K90 they were almost constant despite the identical range of ankle joint motion. These results suggested that MG fascicle behavior during eccentric actions was markedly affected by the knee joint angle. The difference in the fascicle behavior between K0 and K90 could be attributed to the non-linear force–length relations and/or to the slackness of tendinous tissues.

Keywords: Achilles tendon force; Tendinous tissues; Ultrasonography

1. Introduction

Length changes of muscle fibers (fascicles) have been shown to be not always the same as those of a muscle–tendon complex (MTC) due to the elasticity of tendinous tissues (external tendon and aponeurosis) (Griffiths, 1991; Fukunaga et al., 2001; Kawakami et al., 2002). Since the force generating potential of a fascicle is dependent on its length (Gordon et al., 1966) and velocity (Hill, 1938), earlier studies have focused on the fascicle behavior of major exercising muscles in various movements such as walking (Fukunaga et al., 2001; Ishikawa et al., 2005), running (Ishikawa et al., 2007; Lichtwark et al., 2007) and jumping (Kurokawa et al., 2001, 2003; Sousa et al., 2007).

In the previous studies cited above, length changes of the fascicles have been demonstrated to be different between synergists [medial gastrocnemius (MG) and soleus (SOL)] during the lengthening phase of MTC in walking (Ishikawa et al., 2005) and drop jumping (Sousa et al., 2007). For example, during the late-stance phase of walking, MG fascicle was maintained at a near-constant length, while SOL fascicle was elongated (Ishikawa et al., 2005). The different fascicle behavior between MG and SOL may be related to the anatomical difference; i.e., MG crosses the knee and ankle joints, but SOL crosses only the ankle joint. Actually, Kawakami et al. (1998) have reported that the shortening of MG fascicles during maximal static plantar flexions is decreased at flexed knee positions, whereas that of SOL fascicles is similar at different knee joint positions. In addition, our recent study has demonstrated that the length and shortening velocity of MG

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