Materials: Fitness and Conditioning

Theoretical Maximal Pedaling Torque Is Proportional to Fat-Free Soft Tissue Mass of the Lower Extremities in Male Soccer Players

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This study aimed to determine whether theoretical maximal pedaling torque (T_0), obtained from a force-velocity (F-V) test using a cycle ergometer, is proportionally related to fat-free soft tissue mass (FFSTM) of the lower limbs in male soccer players. Forty collegiate male soccer players underwent dual-energy X-ray absorptiometry (DXA) to assess legs FFSTM and performed both a 10-s Wingate test and a F-V test on an electromagnetically braked ergometer. Torque-cadence relationships from the F-V test were used to calculate T_0. Correlation and linear regression analyses were used to evaluate the relationships between T_0 or the torque derived from a 10-s Wingate test (T_{Win}) and legs FFSTM. Proportionality was assessed by testing whether the regression intercept differed significantly from zero. T_0 showed a significant positive correlation with legs FFSTM (r = 0.689, p<0.001), and the regression intercept did not differ significantly from zero, indicating a proportional relationship. In contrast, although T_{Win} also correlated significantly with legs FFSTM (r = 0.755, p<0.001), its regression intercept differed from zero, and T_{Win} /FFSTM negatively correlated with legs FFSTM (r = –0.400, p = 0.010), violating the proportionality assumption. The current results suggest that T_0 is proportionally related to lower limb FFSTM in male soccer players, validating its normalization to legs FFSTM.

Keywords: maximal anaerobic power test, wingate test, DXA, torque-cadence relationship

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1. Introduction

Ball sports athletes frequently perform linear sprints, change-of-direction (COD) movements, and jumping actions during games (Kai et al., 2021; Murtagh et al., 2019; Tenga et al., 2010). One of the fundamental physical capacities underlying these movements is maximal voluntary strength (MVS). Indeed, in soccer players, maximal squat strength, as measured by one-repetition maximum (1RM), has been shown to be strongly associated with sprint performance and vertical jump height (Wisløff et al., 2004). Furthermore, ball sport athletes with greater lower-limb MVS have superior sprinting, COD, and jumping compared to those with lower MVS (Freitas et al., 2019). Additionally, elite soccer players possess higher lower-limb maximal strength than their sub-elite counterparts (Cometti et al., 2001; Gissis et al., 2006). MVS is closely related to muscle size (Akagi et al., 2009; Ikai and Fukunaga, 1968; O'Brien et al., 2009), and the ratio of MVS to muscle size, referred to as muscle quality, has been reported to predict the magnitude of strength gains during the early phase of resistance training, with individuals exhibiting lower muscle quality demonstrating greater improvements (Zou et al., 2023). Therefore, evaluating MVS in ball sport athletes may be beneficial for monitoring conditioning status, assessing the potential for strength adaptation through resistance training, and screening for prospective athletes.

MVS can be assessed using various methods, such as isometric, isokinetic, and one-repetition maximum (1RM) tests. While evaluating MVS across multiple muscle groups is desirable for comprehensive assessment in athletes, practical constraints such as limited time for regular training necessitate simpler yet reliable measurement methods. The force-velocity test using a cycle ergometer is widely employed due to its safety, convenience, and reproducibility, making it a useful tool for evaluating the force-generating capacity of the lower limbs (Arsac et al., 1996; Dorel et al., 2005; Driss et al., 2002). This test derives several indices based on the relationships among pedaling rate, torque, and power output: maximal power (P_{max}), optimal cadence (C_{OPT}) at which Pmax is attained, estimated maximal torque (T_0), and estimated maximal cadence (C_0). P_{max} has been shown to predict both sprint cycling performance and vertical jump height (Dorel et al., 2005; Vandewalle et al., 1987). C_{OPT} is associated with the muscle fiber composition of the knee extensor muscles (Hautier et al., 1996; Vandewalle et al., 1987), and T_0, which represents the theoretical maximal torque extrapolated to zero velocity, correlates with both isometric and isokinetic maximal strength (Driss et al., 2002). Furthermore, studies involving elite cyclists and individuals who regularly engage in cycling suggest that lower limb muscle size may be a key determinant of pedaling torque (Dorel et al., 2005; Lanferdini et al., 2023). However, the obtained indices derived from the force-velocity test differ by sports event (Vandewalle et al., 1987), and since soccer players are not accustomed to pedaling, it is unclear whether the same findings observed in cyclists are applicable to soccer players.

Curran-Everett (2013) emphasized that ratio-based indices, such as MVS per unit muscle size, are statistically appropriate only when a strict proportional relationship exists between the numerator and denominator variables. Otherwise, such normalization introduces systematic bias that distorts inter-individual comparisons. In other words, in addition to a significant correlation between MVS and muscle size, the regression line derived from their relationship must pass through the origin. This implies that individuals with larger muscles may have their MVS per unit of muscle size either underestimated or overestimated. While previous studies have reported significant correlations between T_0, obtained from the force-velocity test using a cycle ergometer, and lower limb muscle size (Dorel et al., 2005; Lanferdini et al., 2023), it remains unclear whether these variables exhibit a proportional relationship. Therefore, the aim of this study was to test the hypothesis that T_0, derived from a force-velocity test using a cycle ergometer, is proportionally related to lower limb muscle size in soccer players. If this proportional relationship is confirmed, T_0 could be validly normalized to muscle size, enabling more accurate inter-individual comparisons of lower limb strength and practical application in performance screening and training evaluation.

2. Methods

2.1. Participants

Forty collegiate male soccer players participated in this study. The physical characteristics of the participants are shown in **Table 1**. All participants participated in regular event-specific training for more than five days (>1.5 h/day) per week for at least 6 years. The inclusion criterion for the participants was categorized from trained (Tier 2) to highly trained (Tier 3) athletes (McKay et al., 2022), which corresponds to that from regional to national level. They were free of cardiovascular, metabolic, and immunologic disorders and/or orthopedic abnormalities, and were not using any medications that affected their muscle function. This investigation was conducted according to the Declaration of Helsinki and was approved by the local Ethics Committee for human experimentation (No. 23-1-41). Prior to the experiment, all participants were informed of the experimental procedures of this study and the possible risks of the measurements beforehand. Written informed consent was obtained from each participant.

2.2. Experimental design

Data collection was conducted immediately after the end of an in-season from late November through December. All participants visited the laboratory on the two different sessions. Room temperature was maintained at 22 °C throughout all sessions. Body composition and anaerobic pedaling test were measured in one session, and a 10-s maximal sprint cycling test was measured in another session. The specific methods for each measurement were described below.

Table 1 Descriptive data on the measured variables

	Means		SDs	Min	Max
Age, years	20.6	±	1.5	18.9	27.6
Body height, cm	172.2	±	5.5	162.9	182.6
Body mass, kg	67.2	±	5.9	53.2	77.8
BMI, kg/m^2	22.7	±	1.6	19.4	26.1
%FM	11.4	±	3.1	7.6	19.7
FFSTM					
Whole body	55.6	±	4.6	45.9	65.9
Legs	19.5	±	1.8	16.5	23.8
10-s Wingate test					
T_{Win}, Nm	47.1	±	4.2	37.5	55.0
T_{Win}/BM, Nm/kg	0.70	±	0.02	0.62	0.73
P_{Win}, w	808	±	93	605	989
P_{Win}/BM, w/kg$^{2/3}$	48.8	±	3.6	41.5	56.0
Force-velocity test					
T_0, Nm	150.1	±	21.0	109.5	190.5
T_0/BM, Nm/kg	2.23	±	0.26	1.77	2.73
C_0, rpm	233.7	±	11.2	208.9	254.8
C_{OPT}, rpm	116.4	±	5.6	104.1	127.0
P_{max}, w	937	±	137	697	1184
P_{max}/BM, w/kg$^{2/3}$	56.6	±	6.7	45.4	69.8

Values are expressed as means and SDs.
BM, body mass; BMI, body mass index; %FM, percent body fat;
FFSTM, fat-free soft tissue mass
T_{Win}, pedaling torque derived from the 10-s Wingate test
P_{Win}, pedaling power derived from the 10-s Wingate test
T_0, theoretical maximal pedaling torque
C_0, theoretical maximal pedaling cadence
C_{OPT}, optimal pedaling cadence
P_{max}, theoretical maximal pedaling power

2.3. Anthropometry and body composition

Body height and body mass were measured using a stadiometer and a digital weight scale to the nearest 0.1 cm and 0.1 kg, respectively. Whole body and regional fat mass (FM), fat-free soft tissue mass (FFSTM) and percent fat mass (%FM) were measured with a DXA scanner (Hologic Delphi A-QDR, USA). Participants lay supine on a bed with arms and legs straight. Room temperature was usually kept at 22 °C, according to an earlier study. The reproducibility of the DXA measurement was described in an earlier study (Takai et al., 2020).

According to the previous study (Zemski et al., 2015), the body was divided into four segments: the head, trunk, arms and legs with built-in software from the obtained radiography (Hologic Delphi A-QDR, USA). The arms were separated from the trunk by localizing a cut through the axilla and to the medial head of the humerus. The head was separated from the trunk by cutting just below the mandible. The legs were separated from the trunk by positioning an angle cut through the bottom of the ischium, forming a triangle with the supracrestal line. Legs FFSTM was the sum of the right and left legs.

2.4. Anaerobic pedaling power test.

Participants pedaled with maximal effort for <7 s on an electromagnetically braked cycle ergometer (POWERMAX VIII, KONAMI) against 6 loads (1, 3, 5, 7, 9, and 10 kp). The saddle height of the cycle was adjusted such that when the crank position was in the dead center at the bottom and the foot was secured to the pedal with toe clips, the knee joint was near full extension (approximately 170-175°). We asked participants to pedal maximally and to maintain pedaling cadence as high as possible for ~7 s and were verbally encouraged by the examiners. Since participants attempt to pedal with maximal effort comfortably, participants were not required to keep their hips in contact with the saddle; lifting the hips during pedaling was permitted. Prior to a main testing session, the participants performed a standardized warm-up protocol (stretching and a 5-min cycle exercise with a load of 50 w at 70 rpm) and a familiarization session consisting of 3 sprints of ~7 s epoch (1, 5, and 10 kp) with an interval of 1 min. The anaerobic power test consisted of 6 sprints for ~7 s, interspersed with 5-min periods. The trial order was randomized across participants. One person could not pedal against loads of 9 and 10 kp, so he did against 1, 2.5, 4, 5, 6, and 7 kp. A maximal power and cadence for each load were recorded.

As seen in **Fig. 1**, each participant's power-cadence relationship was fitted using second-order polynomial regressions with a fixed y-intercept set at zero. From the quadratic equation, the maximal power (P_{max}) and optimal cadence (C_{OPT}) were computed, which corresponds to the y- and x-coordinates of the apex of the corresponding relationship. Furthermore, the torque pedaled in each trial was calculated from the power and cadence in each load as follows:

$$torque_{(Nm)} = power_{(W)} \times 9.549 / cadence_{(rpm)} \quad (1)$$

The torque-cadence relationship was fitted using linear regression, and the slope and x- and y-intercepts from the regression line were computed, which were defined as torque-cadence profile, theoretical maximal pedaling torque (T_0, Nm) and theoretical maximal cadence (C_0, rpm).

2.5. Ten seconds maximal sprint cycling test

According to the method described in Yoshimoto et al. (2019), the participants performed a 10-s maximal sprint cycling test using an electro-magnetically braked cycle ergometer (POWERMAX-VIII, COMBI

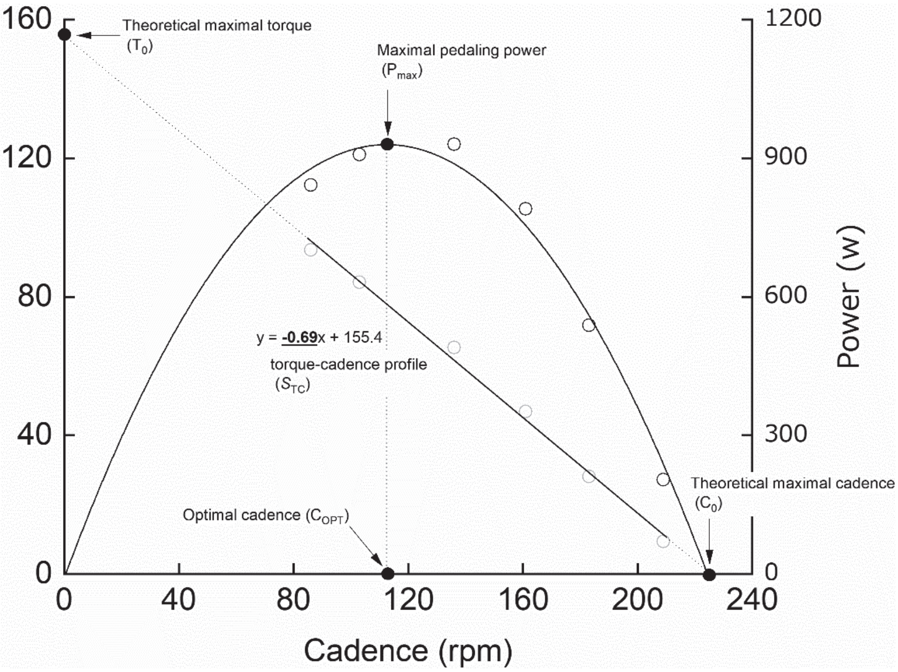

Figure 1 Calculation of theoretical maximal pedaling torque (T_0), maximal cadence (C_0), torque-cadence profile (S_{TC}), and maximal pedaling power (P_{max}) derived from the torque-, cadence- and power-relationships in a representative participant.

Wellness, Japan) to assess the maximal anaerobic pedaling power. The testing posture and instruction for participants were identical to those used in the anaerobic pedaling power test. The load of 7.5% of body mass was applied as a flywheel resistance in the test. The trials were conducted twice with a 5-minute rest between trials. The highest maximal pedaling power was adopted as the representative value. Peak pedaling power was computed from the peak cadence, and these values were then used to derive the peak torque (T_{Win}) according to Eq. (1).

2.6. Statistical analysis

Descriptive data are means and standard deviations (SDs). The independent variables were legs FFSTM, T_{Win}, and T_0. The Shapiro-Wilk test was performed to confirm the normality of the independent variables. As a result, the normality of all the variables was confirmed. Pearson's product-moment correlation coefficient (r) was calculated to examine the relationships between T_{Win} and legs FFSTM as well as between T_0 and legs FFSTM. The simple regression analysis was also performed to examine whether the y-intercept of the linear regression line differs from zero. The magnitude of the correlation between performance and training load variables was assessed with the following thresholds: <0.1, trivial; 0.1<0.3, small; 0.3<0.5, moderate; 0.5<0.7, large; 0.7<0.9, very large; 0.9<1.0, almost perfect (Hopkins, 2006). The p value was computed with a statistical software (SPSS Statistics ver. 26, IBM Corporation, Japan). Statistical significance was set at 0.05.

3. Results

The relationship between either T_0 ($r = 0.689$, $p = 0.001$) or T_{Win} ($r = 0.755$, $p = 0.001$) and legs FFSTM was significant and positive (**Fig. 2**). The y-intercept derived from the relationship between T_0 and legs FFSTM did not significantly differ from zero ($t = 0.252$), but the y-intercept from the relationship between T_{Win} and legs FFSTM was significantly different from zero ($t = 3.795$). No significant correlation was found between T_0/legs FFSTM and legs FFSTM ($r = 0.036$, $p = 0.826$), but there was a significant relationship between T_{Win}/legs FFSTM and legs FFSTM ($r = -0.400$, $p = 0.010$).

4. Discussion

The main finding of this study is that theoretical maximal pedaling torque (T_0) was proportional to legs fat-free soft tissue mass (FFSTM) in soccer players, and T_0/legs FFSTM was not significantly related to the magnitude of legs FFSTM. The findings suggest that T_0 is validly normalized to legs FFSTM, enabling more accurate inter-individual comparisons of force generating capacity of lower limb and practical application in training adaptation.

As depicted in **Table 1**, force-velocity profile derived from the force-velocity test by using an electromagnetically braked cycle ergometer were 150.1 ± 21.0 Nm for T_0, 233.7 ± 11.2 rpm for C_0, 116.4 ± 5.6 rpm for C_{OPT}, and 937.3 ± 136.9 W for P_{max}. The values obtained in this study fall within the range reported for soccer players (Nikolaidis and Knechtle, 2021) but are lower than those reported for sprint cyclists (Dorel et al., 2005). Additionally, the relationship between either T_0 ($r = 0.689$) or T_{Win} ($r = 0.755$) and legs FFSTM was significant and positive (**Fig. 2**). The correlation coefficients in this study are similar to the coefficient reported by a previous study of world-class cyclists (0.77) (Dorel et al., 2005). Based on the above findings, the force-velocity test used in this study appears to have effectively assessed the mechanical power characteristics of pedaling in the population examined here.

The intercept of the regression equation between T_0 and legs FFSTM was not significantly different from zero. Additionally, T_0/legs FFSTM was not significantly correlated with legs FFSTM. The current results indicate that the relationship between T_0 and legs FFSTM satisfies the statistical assumption of proportionality (Curran-Everett, 2013), supporting the validity of using T_0 per unit of fat-free soft tissue mass as an index of muscle quality. In contrast, when considering time efficiency in strength measurement, the Wingate test which requires only a single load, may offer practical advantages. In this study, although a significant correlation was found between T_{Win} and legs FFSTM, the normalized value (T_{Win}/legs FFSTM) showed a significant negative relationship with legs FFSTM. This indicates that individuals with greater legs FFSTM tend to have lower values of T_{Win}/legs FFSTM, leading to underestimation and violating the assumption of proportionality (Curran-Everett, 2013). Taken together, the current findings suggest that T_0 derived from the force-velocity test may serve as a

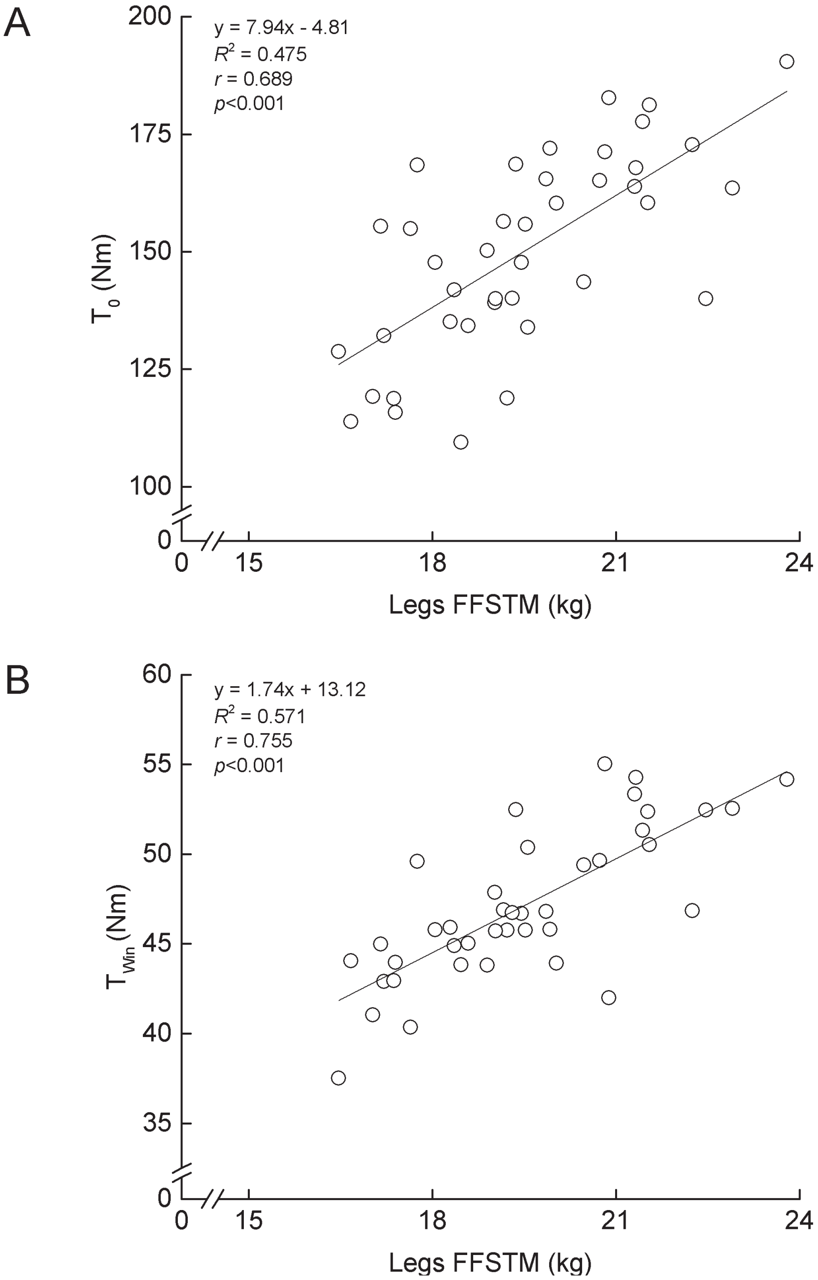

Figure 2 Relationships between theoretical maximal pedaling torque (T_0) and legs fat-free soft tissue mass (FFSTM) (A), and between pedaling torque derived from the 10-s Wingate test (T_{Win}) and legs FFSTM (B).

valid indicator of maximal muscle strength in lower limbs.

Since the intercept of the regression equation differed significantly from zero, T_{Win} obtained from the 10-s maximal sprint cycling test was not proportional to legs FFSTM. In high-trained athletes, a single load test (8.7% of body mass) has been reported to yield lower peak power values by approximately 30% than those derived from a multiple-load test (Jaafar et al., 2016). In this study, peak power calculated from the single-load protocol was 13% lower than the P_{max} from the multiple-load method. The load used in the 10-s maximal sprint cycling test was 5 kp (range: 4-5.8 kp), which was lighter than the load at which maximal power derived from the anaerobic pedaling power test (7.6 kp, range: 5.7-9.3 kp). Although we could not elucidate the physiological or biomechanical factors why pedaling torque measured at a suboptimal load fails to scale proportionally with leg FFSTM, the 10-s maximal sprint cycling test used here likely contains bias due to the use of a load below the optimal load.

Prior to concluding, it is important to acknowledge a few limitations of this study. First, the participants were limited to soccer players. Since mechanical variables obtained from the force-velocity test may vary depending on the sport discipline (Vandewalle et al., 1987), it remains unclear whether these findings are generalizable to athletes in other sports. Second, in the multiple-load protocol, participants performed six bouts of maximal pedaling (<7 s each), which could plausibly induce fatigue and affect the torque–cadence relationship. Nevertheless, the correlation coefficients for each participant (-0.966 to -0.999) indicated an extremely strong relationship, suggesting that fatigue effects were likely small. Third, while our results suggest that T_0/leg FFSTM might be useful as a screening index for anticipating individual differences in strength gains of resistance training, given that adaptation may vary with maximal strength relative to muscle size (Zou et al., 2023), this potential application requires confirmation in longitudinal and intervention-based studies.

5. Conclusion

Theoretical maximal pedaling torque is proportional to fat-free soft tissue mass of the lower extremities in male soccer players.

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Disclosure of interests

None of the authors have any conflict of interest.

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