Muscle Stiffness and Rate of Torque Development during Sprint Cycling

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ABSTRACT

WATSFORD, M., M. DITROILO, E. FERNÁNDEZ-PEÑA, G. D'AMEN, and F. LUCERTINI. Muscle Stiffness and Rate of Torque Development during Sprint Cycling. *Med. Sci. Sports Exerc.*, Vol. 42, No. 7, pp. 1324–1332, 2010. **Purpose**: Crank torque (CT) application and rate of CT development (RCTD) are important considerations in sprint cycling. The stiffness of the musculotendinous unit is related to the isometric rate of torque development (RTD); however, this relationship has yet to be examined in sprint cycling. **Methods**: Maximal isometric torque (MIT) and isometric RTD of the quadriceps were assessed in 21 trained male cyclists (28.7 ± 9.5 yr, 1.74 ± 0.08 m, and 67.5 ± 7.2 kg). Unilateral musculoarticular (MA) stiffness of the quadriceps was quantified using an oscillation test. Further, the participants performed a maximal 6-s sprint to assess peak power output (PO_{peak}), peak CT (CT_{peak}), peak RCTD ($RCTD_{peak}$), and the crank angles associated with CT_{peak} and $RCTD_{peak}$. Participants were ranked on MA stiffness properties and were divided into a relatively stiff group (SG) and a relatively compliant group (CG). **Results**: The SG displayed a significantly higher MA stiffness than the CG ($P < 0.05$). Furthermore, the SG reported significantly elevated MIT (27%), RTD (26%), and $RCTD_{peak}$ (16%) when compared with the CG ($P < 0.05$), along with trends for increased PO_{peak} (7%) and CT_{peak} (8%). The angles at CT_{peak} and $RCTD_{peak}$ were 7% and 12% lower for the SG, respectively ($P < 0.05$). MA stiffness was significantly correlated with $RCTD_{peak}$, MIT, RTD, and PO_{peak}. **Conclusions**: Higher stiffness is related to superior $RCTD_{peak}$ in trained cyclists during a single sprint. A significant proportion of the variance in $RCTD_{peak}$ was attributed to MA stiffness (37%), which was of greater magnitude than the relationship between $RCTD_{peak}$ and MIT. Furthermore, the lower CT_{peak} angle and $RCTD_{peak}$ angle may contribute to a more rapid development of CT. Accordingly, MA stiffness seems to be an important consideration for sprint cycling. **Key Words:** MUSCLE–TENDON UNIT, ELASTICITY, RATE OF FORCE PRODUCTION, ISOMETRIC TORQUE

Sprint cycling performance is dependent on many different physiological and biomechanical parameters. Considering the biomechanical parameters, it has been clearly demonstrated that peak power output (PO_{peak}), crank torque (CT), crank length, and cadence are all determinants of superior sprint performance (12,14,29). There is a possibility that cycling propulsion, and, accordingly, sprint performance, may be enhanced after an improvement in parameters that relate to these variables.

Whereas maximal muscle force output is normally reached in greater than 300 ms, the ability to quickly produce muscular force, which is commonly expressed as rate of torque development (RTD), has been demonstrated as a factor determining performance in several explosive sports involving movements with fast contraction times (50–250 ms) (1). Accordingly, it is of paramount importance for most athletes to be able to rapidly raise the level of muscle force in the early phase of contraction. RTD, therefore, has an impact in sports such as handball (37), sprint running (27), tennis (27), karate, and jumping (2).

Cycling requires force application onto the pedal surface. Most of the propulsion relies on the downward phase of the pedaling revolution. The force arises, starting from the top dead center, reaching a maximum around 110°, declining thereafter (34). Pedal forces have been measured to be 340 N when pedaling at 90 rpm at 80% of maximal power output (33) or up to 1100 N during sprint cycling (11). The time available to generate such high levels of force depends on the cadence. When pedaling at a cadence of 80 rpm or

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higher, as generally occurs in cycling competitions (23), the time to peak force is less than 250 ms. Sprint cycling performance, therefore, requires a high CT to be rapidly developed as a steeper torque profile while sprinting would manifest in a greater impulse and initial torque transmission capacity. Conceivably, it can be maintained that the rate of CT development (RCTD) is a special case of RTD.

Owing to the reliance on concentric power and torque development during cycling, especially during periods of sprinting and transition to sprinting, a higher stiffness may improve the RCTD. In relation to this point, Wilson et al. (41) theorized that because an activity such as cycling would benefit from a more rapid transmission of concentric force, higher musculotendinous stiffness may indeed be related to improved performance. A proposed improvement in force–velocity characteristics, along with improved transmission of initial force (41), may have direct benefits for CT development and overall performance velocity.

Stiffness refers to a body resisting an applied change in length and is calculated as the ratio of change in force to change in length (4). Stiffness has typically been presented in the literature with reference to Hill's three-component model of muscle (35,43). Much of the elasticity reportedly resides in the series elastic component (SEC), making this region a primary contributor to stiffness. Direct, isolated measures of SEC stiffness have been previously reported (30) and termed musculotendinous stiffness. Further development of such testing procedures has led to the quantification of active musculoarticular (MA) stiffness. This measure quantifies the stiffness of the SEC along with that of the surrounding articular surfaces, ligaments, and skin (32) and is often assessed using a free oscillation technique.

Because of the variation in nomenclature for stiffness, care must be taken when comparing previous studies. It seems that the terms "musculotendinous stiffness" and "MA stiffness" have been used interchangeably in the literature; therefore, when interpreting the results from previous studies, differences in stiffness assessment methodologies must be considered. It is clear, however, that the musculotendinous unit is the primary link between the contractile properties of muscle and the movement capabilities of the skeletal system (41). Accordingly, the mechanical properties of the musculotendinous unit determine the force transmission and force dissipation characteristics of skeletal muscle (42). Elevated stiffness may provide a greater tensile force per unit of length change, with a resultant elevation in RTD. In fact, it has been reported that musculotendinous stiffness is integrally related to performance in different sporting activities including jumping and sprint/distance running (36,38,41). Given the assessment methods presented in the above studies, the authors actually assessed MA stiffness. Generally, these activities rely on the use of a stretch shorten cycle to aid movement efficiency; however, MA stiffness has also been integrally linked with concentric-only rate of force development (28,38,41). Therefore, such a relationship may also be relevant to a repetitive, concentric-only action such as cycling.

To the best of our knowledge, the relationship between MA stiffness and RCTD is yet to be examined, and such information will be of interest to cyclists, coaches, and conditioning specialists from a variety of sports. Recent research has outlined the possibilities of modifying stiffness with appropriate training. Weight training (20), isometric training (7,21), eccentric training (30), and plyometric training (7,36) have all displayed positive influences on tendon stiffness, joint stiffness, or MA stiffness. Therefore, a greater understanding of the relationship between stiffness and cycling may provide opportunities to modify favorably MA stiffness to improve cycling performance. Specifically, the aim of this research was to examine the relationship between MA stiffness and RCTD during cycling. Because higher stiffness has been related to elevated RTD in other activities, it was hypothesized that cyclists with higher MA stiffness would yield a superior RCTD, with concomitant benefits for sprint cycling performance.

METHODS

Research Design

In this descriptive study, trained cyclists were divided into two significantly different groups according to their quadriceps MA stiffness characteristics. One group included the relatively stiff cyclists (SG) and the other group contained the more compliant cyclists (CG). Mechanical variables related to isometric torque production and cycling sprint ability were then compared between the two groups. Further, MA stiffness values were correlated with performance variables to determine any relationship.

Participants

Twenty-one trained male competitive cyclists (28.7 ± 9.5 yr, 1.74 ± 0.08 m, and 67.5 ± 7.2 kg) volunteered to participate in this project and provided written informed consent. They were currently undertaking a cycling training program covering 409 ± 212 km in 5.5 ± 1.8 sessions per week and had a mean ± SD of 11.8 ± 8.0 yr of cycling experience. Participants with a range of cycling ability were recruited, including under-23, elite, masters, and professional cyclists, along with two well-trained triathletes. The two triathletes had competed in cycling competitions previously and were currently undertaking cycling-specific training where the volume did not differ from the other subjects. Recruitment of a variety of levels of cyclists permitted the examination of MA stiffness characteristics across a spectrum of physical abilities. Participants arrived at the laboratory in a rested state, having been asked to refrain from exercise in the preceding 24 h. They were screened using a medical questionnaire and were excluded from the research if they had suffered a recent significant soft tissue injury to the leg or reported other significant health issues. The ethics committee at the University of Urbino, Italy, approved the research.

Testing Procedures

In one testing session, maximal isometric torque (MIT), RTD, and MA stiffness were assessed in the musculature of the quadriceps of the participant's preferred leg. This muscle group was selected because of its role in cycling, with the quadriceps being active between 337° and 134°, when considering a complete revolution of the pedaling action to be from 0° at top dead center (29). Accordingly, the quadriceps are the primary source of CT production during the downstroke phase of cycling (13,31). The participants were also assessed for peak PO (PO_{peak}), peak CT (CT_{peak}), and peak RCTD ($RCTD_{peak}$) on a bicycle ergometer during a 6-s sprint. Further, the crank angles where CT_{peak} (CT_{peakA}) and $RCTD_{peak}$ ($RCTD_{peakA}$) occurred were assessed, along with the impulse of the first half of the downstroke during pedaling (Impulse-90). After a warm-up, the MIT/RTD assessment was performed first for all participants, followed by the MA stiffness assessment and, finally, the sprint cycling test.

Warm-up

A standard warm-up was used at each test occasion because a warm-up has been demonstrated to affect stiffness (25). Before the MIT test, participants performed a 6-min warm-up consisting of cycling at 100 W for 3 min and 150 W for a further 3 min. Before the cycling test, a further 6 min of cycling was prescribed at 150 W to prepare the participants for the maximal sprint test and to wash out any potential effects of the MIT test.

Isometric Strength and RTD

A unilateral knee extensor strength test was performed on a leg extension dynamometer (Technogym, Gambettola (Fo), Italy) using the participant's preferred leg. Each cyclist was asked to state which leg felt more comfortable when required to exert maximum force on the pedals. Subsequently, this leg was used for the MIT and MA stiffness assessments. As depicted in Figure 1, the participant sat in the seat with a hip angle of 90° and a knee angle of 100°. The lateral femoral condyle was aligned with the axis of the dynamometer, and the force transmission point was a bar that was positioned anterior to the participant's lateral malleolus, thus maximizing the length of the lever arm. The weight stack of the device was fastened to prevent any movement, thus eliciting an isometric contraction when the participant extended the leg. After familiarization with the device, the participant was instructed to produce as much force with the quadriceps, as quickly as possible, for approximately 4 s. Strong verbal encouragement was offered for the duration of the test. Arms were held across the chest to prevent any contribution from the upper body, and participants were secured at the hips with a belt to prevent hip extension during the test.

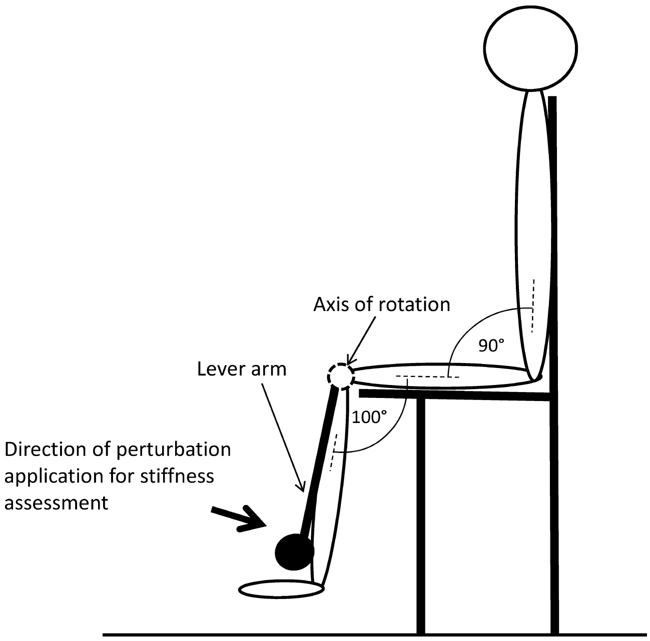

FIGURE 1—Schematic diagram of the position for the unilateral MIT and MA stiffness assessment. For the MIT test, the lever arm was fixed to record isometric torque. For the MA stiffness assessment, the lever arm was free to oscillate after the application of a perturbation.

Force data were recorded by a load cell (Leane International, Parma, Italy; measurement range = 0–750 kg, output = 2.92 $mV \cdot V^{-1}$) placed in series with the direction of force application. A minimum of two trials were conducted for each participant, with the best result used for analysis. A 2-min rest was permitted between trials. To eliminate high-frequency noise associated with the data acquisition system (a 16-bit A/D converter; APLabDAQ, APLab, Rome, Italy), the load cell signal was filtered online using a third-order, zero-phase Butterworth low-pass filter at a 300-Hz cutoff frequency and was then sampled at 10 kHz. Before data analysis, the load cell signal was filtered offline using a 5-ms moving average. Torque was calculated by multiplying the force by the length of the lever arm, with the highest torque value considered as MIT. The isometric RTD was calculated using the average slope of the torque profile from 0 to 100 ms and from 0 to 300 ms. This method has been previously validated and has demonstrated good to excellent levels of reliability (1).

MA Stiffness

Lower body MA stiffness was assessed using a free oscillation technique that has been described on numerous occasions as a valid and reliable method of quantifying stiffness (16,24,26,28,35). The oscillation technique involves the assumption that human muscle is modeled as a damped spring–mass system and that any perturbation to a loaded system will result in oscillations containing a damping element due to the viscoelastic properties of the muscle and tendon (35).

According to Shorten (35) and Wilson et al. (42), the system will oscillate at its natural frequency regardless of the magnitude of the perturbation. The oscillations are then modeled according to a second-order linear equation considering the frequency of oscillation and the damping coefficient. The damped natural frequency is determined from the interval between the first complete sinus cycles displayed as successive maximum amplitude peaks. The change in amplitude between successive peaks, measured in force or gravitational force, is then used to calculate the coefficient of damping. With these two values, and the knowledge of the mass being supported by the subject, the stiffness of the lower body may be calculated (26,35). For a more detailed description of these calculations, readers are referred to the work of McNair et al. (26) and Walshe et al. (39).

Quadriceps MA stiffness assessment was performed on the leg extension dynamometer in a position that was identical with that used in the MIT assessment, i.e., 100° at the knee (Fig. 1). The participants supported a load on the distal portion of the anterior lower leg, which corresponded to 50% of their MIT. A brief perturbation of the order of 100–150 N was applied, and the ensuing oscillations were recorded by a uniaxial accelerometer (Crossbow San Jose, CA) attached to the distal end of the moveable lever arm of the dynamometer. Such methods were based on the work of Granata et al. (16); however, the current design incorporated (a) a reduced knee angle (100° vs 135°), potentially increasing the parallel elastic component contribution to stiffness, and (b) a greater assessment load (50% of MIT vs 20% of maximum voluntary exertion). Such methodological differences would potentially increase the magnitude of MA stiffness in the current study when compared with those in the study of Granata et al. (16). Data were sampled at 1000 Hz and recorded to a personal computer using a 16-bit A/D conversion. For each participant, two trials were completed, and the results were averaged for analysis. One minute of rest was prescribed between trials. For processing, data were filtered using a Butterworth low-pass filter (third order) with a cutoff frequency of 6 Hz. The linear stiffness was transformed to a rotational stiffness with multiplication by the length of the lever arm. This test displayed excellent interday reliability (unpublished data), with a typical error of measurement (17) of 3.8% and intraclass correlation coefficient of 0.977 ($P < 0.001$).

Cycling Performance

PO_{peak}. A 6-s sprint cycling exercise was performed by each participant on an SRM ergometer (Schoberer Rad Meßtechnik GmbH, Jülich, Germany) to determine their PO_{peak}. The ergometer was set to the isokinetic mode, with cadence fixed at 80 rpm. The SRM crank set, equipped with strain gauges, directly measured the torque produced by the force applied to the pedals perpendicularly to the crank. The participant's own bicycle measurements were used to customize the ergometer for seat height, seat setback, and crank length, and participants used their own cycling pedals and shoes.

Before the maximal sprint, the participants were required to pedal at a low intensity (50–100 W) and, after a start signal, were required to pedal as forcefully as possible for 6 s. Strong verbal encouragement was provided throughout the test. Power measurements were calculated from the SRM crank set, with sampling at 200 Hz. PO_{peak} of each maximal trial was calculated as the product of the average torque of the best five pedal revolutions (N·m) and their actual cadence ($rad{\cdot}s^{-1}$). Each participant completed two to three maximal sprints, with 3 min of recovery between efforts. The test, which recorded the highest PO_{peak}, was used for analysis. Detailed methodology for this test has been described elsewhere, along with the reporting of excellent reliability and validity (15).

CT_{peak} and RCTD. To provide a detailed understanding of CT production during sprint cycling, the mean of the five pedal revolutions exhibiting the highest peak torque was chosen for analysis. This was deemed to be more relevant to performance than simply selecting the highest singular revolution. CT_{peak} was the highest value recorded from the downstroke of the CT data during the pedal revolutions, and instantaneous $RCTD_{peak}$ was calculated as the highest rate of change in the CT values for each pedal revolution. Because the measurements were taken on the preferred leg only for each participant, downstroke CT data for right-legged participants were assessed between 0° and 180°, and those for left-legged participants were assessed between 180° and 360°. The average RCTD ($RCTD_{ave}$) production was also assessed by dividing the change in CT (CT_{peak} minus minimum CT) by the time taken to reach CT_{peak} from the minimum CT value, measured in seconds. To provide a further tool to examine changes in torque production profile, the Impulse-90 was recorded from the commencement of the pedal revolution to an absolute angle of 90° for all participants. To examine any changes in CT profile, the CT_{peakA} and the $RCTD_{peakA}$ were assessed.

Statistical Analyses

Descriptive statistics were calculated using SPSS (version 16, SPSS Inc., Chicago, IL). The participants were divided

TABLE 1. Results for all participants and comparative data for the CG and the SG for anthropometric, stiffness, and isometric torque variables.

Performance Variable	All Cyclists ($n = 21$)	CG ($n = 10$)	SG ($n = 10$)	P	ES (Cohen d)
Age (yr)	28.7 ± 9.5	27.4 ± 9.5	28.3 ± 8.7	0.83	0.10
Stature (m)	1.75 ± 0.08	1.74 ± 0.06	1.75 ± 0.01	0.79	0.13
Body mass (kg)	67.5 ± 7.2	66.6 ± 7.6	68.1 ± 7.4	0.65	0.21
Limb length (m)	0.37 ± 0.02	0.37 ± 0.02	0.38 ± 0.03	0.68	0.19
Quadriceps MA stiffness ($N{\cdot}m{\cdot}rad^{-1}$)	1860.7 ± 698.8	1367.6 ± 186.9	2376.8 ± 691.6*	<0.01	2.30
MIT (N·m)	320.4 ± 72.2	279.2 ± 45.3	355.5 ± 76.6*	0.02	1.25
Isometric RTD 0–300 ms ($N{\cdot}m{\cdot}s^{-1}$)	746.8 ± 149.9	660.6 ± 101.3	831.8 ± 152.8*	0.01	1.35
Isometric RTD 0–100 ms ($N{\cdot}m{\cdot}s^{-1}$)	989.8 ± 390.3	767.5 ± 280.0	1194.5 ± 394.0*	0.01	1.27

Data are mean ± SD.

* Significant difference from CG.

TABLE 2. Results for all participants and comparative data for the CG and the SG for cycling performance variables.

Performance Variable	All Cyclists (*n* = 21)	CG (*n* = 10)	SG (*n* = 10)	*P*	ES (Cohen *d*)
PO$_{peak}$ (W)	795.9 ± 104.5	773.0 ± 89.1	823.8 ± 120.8	0.30	0.48
CT$_{peak}$ (N·m)	144.4 ± 21.3	140.1 ± 18.4	151.1 ± 23.1	0.25	0.53
RCTD$_{peak}$ (N·m·s^{-1})	1301.8 ± 230.5	1213.8 ± 189.0	1411.9 ± 234.2*	0.05	0.94
RCTD$_{ave}$ (N·m·s^{-1})	628.0 ± 147.8	579.1 ± 116.3	703.8 ± 133.8*	0.04	1.00
Impulse-90	7542.7 ± 1239.8	7230.6 ± 1021.1	7927.6 ± 1428.8	0.23	0.57
CT$_{peakA}$ (°)	99.9 ± 8.7	102.3 ± 7.0	95.7 ± 7.3*	0.05	0.93
RCTD$_{peakA}$ (°)	43.2 ± 5.8	45.9 ± 6.7	40.5 ± 3.7*	0.04	1.03

Data are mean ± SD.
* Significant difference from CG.

into two groups on the basis of their quadriceps stiffness rankings. Because 21 cyclists were recruited, the subject exhibiting the stiffness result corresponding to the median value was discharged from the between-group comparisons. The 10 participants exhibiting the highest stiffness values were placed in the SG, and the 10 displaying the lowest stiffness values were placed in the CG. An independent-samples *t*-test was conducted to ensure that this method created two groups with different stiffness characteristics. After this assurance, independent-samples *t*-tests were conducted on all variables to examine the role of MA stiffness in isometric torque production and cycling performance variables. To quantify the magnitude of differences between the groups, measures of effect size (ES) were assessed using Cohen *d* (10). Pearson product–moment correlations were calculated to examine the relationship between quadriceps stiffness and each performance variable. Further, quadriceps MIT production was correlated with each performance variable to examine for any comparable relationships. For all statistical procedures, an α level of $P \leq 0.05$ was used to determine significance, and ES magnitudes were considered to be minimal (<0.3), small (between 0.3 and 0.5), moderate (between 0.5 and 0.7), or large (>0.70).

RESULTS

The mean results for the key performance variables for all participants and the two groups are presented in Table 1. The median split used in the current study divided the sample into two groups with significantly different quadriceps MA stiffness. There were no differences in age, stature, body mass, or lower limb length between the groups.

The SG reported significantly higher MIT (27%) and isometric RTD for the 0–100 ms (56%) and 0–300 ms (26%) conditions when compared with the CG. For the cycling performance variables presented in Table 2, RCTD$_{peak}$ was significantly higher for the SG (16%), whereas PO$_{peak}$ and CT$_{peak}$ tended to be 7% and 8% higher, respectively, with the difference between the two groups yielding a moderate ES. The RCTD$_{ave}$ results were significantly higher for the SG compared with the CG (22%), whereas the Impulse-90 tended to be higher in the SG (10%), with a moderate ES evident. Finally, the SG recorded a 6.6° lower CT$_{peakA}$ and 5.4° lower RCTD$_{peakA}$, which, as depicted by two representative participants from each group in Figure 2, significantly altered the torque profile between the groups.

Figure 3A displays the significant relationships evident between quadriceps MA stiffness and RCTD$_{peak}$ during cycling. As presented in Figures 3B–D, MA stiffness was significantly correlated with isometric RTD (0–300 ms), MIT, and PO$_{peak}$. Furthermore, the correlation analysis between MA stiffness and CT$_{peakA}$ and RCTD$_{peakA}$ revealed moderately negative, yet significant relationships ($r = -0.53$, $P = 0.01$; $r = -0.45$, $P = 0.04$, respectively). The relationship between quadriceps MIT and RCTD$_{peak}$ was also examined, yielding a significantly positive correlation ($r = 0.52$, $P = 0.02$).

DISCUSSION

This study is the first to examine the relationship between MA stiffness and RCTD during cycling. Previous research has highlighted a relationship between stiffness and RTD during isometric and concentric muscular actions, identifying significantly positive relationships between these variables (41). During the downstroke phase of cycling, a faster RCTD would conceivably relate to a more effective CT profile for sprint cycling, hence an improvement in cycling propulsion.

Within the limitations of the current study, MA stiffness was significantly different between the SG and the CG. In congruence with previous research, the SG displayed higher isometric RTD and MIT (28,39). Further,

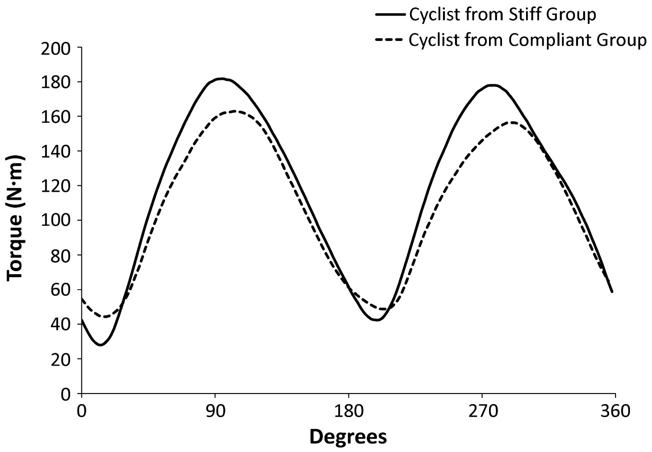

FIGURE 2—Representative cycling torque profiles throughout one complete pedal revolution for one cyclist in the SG and one cyclist in the CG.

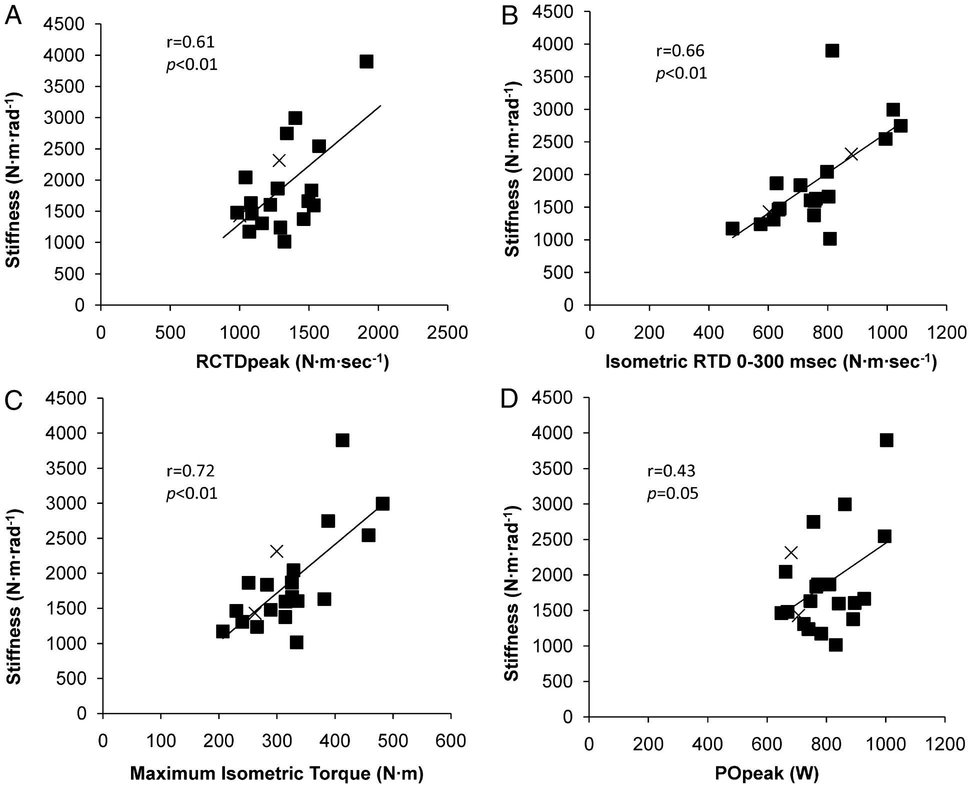

FIGURE 3—Pearson product–moment correlations between quadriceps MA stiffness and $\text{RCTD}_{\text{peak}}$ during cycling (*A*), isometric RTD (*B*), maximum isometric torque (*C*), and PO_{peak} (*D*). The triathletes within the sample are identified as "X."

MA stiffness was significantly correlated with isometric RTD (0–300 ms condition) and MIT (Figs. 3B and C, respectively). A relatively stiffer musculotendinous unit reportedly has a greater capacity for force or torque production owing to an improved force–velocity relationship, improved length–tension relationship, and an improvement in the initial transmission of force (41). Specifically, when considering the length–tension relationship, Wilson et al. (41) postulated that, for a given level of contraction, a stiffer musculotendinous unit will maintain a greater contractile component length when compared with a relatively compliant musculotendinous unit. Such maintenance of a greater sarcomere length may promote an elevated resultant force output. Furthermore, a relatively stiff musculotendinous unit may reduce the electromechanical delay by reducing the amount of time to "take up the slack residing in the tendon" (9), thus improving RTD. The current results provide construct validity for the measure of quadriceps MA stiffness and, along with the low technical error of measurement, demonstrate that the methods applied in the current study were appropriate for the assessment of MA stiffness.

Participants in the SG also showed superior results during the 6-s cycling sprint. $\text{RCTD}_{\text{peak}}$ in the SG was higher, along with RCTD_{ave} (Table 1). Furthermore, the lower CT_{peakA} and $\text{RCTD}_{\text{peakA}}$ in the SG, indicative of a steeper torque profile (Fig. 2), revealed a more effective initial transmission of torque during cycling. The tendency for a higher Impulse-90 is also representative of an improved torque profile during sprint cycling. Moderate, negative correlations were evident between MA stiffness and CT_{peakA} ($r = -0.53$, $P = 0.01$) and $\text{RCTD}_{\text{peakA}}$ ($r = -0.45$, $P = 0.04$), which emphasize these findings. Each of these factors are related to the three mechanical factors relating to force–velocity, length–tension, and initial force transmission relationships, as postulated by Wilson et al. (41), and indicate that a relatively high level of quadriceps MA stiffness may improve sprint cycling ability. The achievement of $\text{RCTD}_{\text{peak}}$ earlier in the crank cycle is conceivably beneficial to sprint performance, given that sprint cycling tends to produce a torque profile with more emphasis placed on a high force application during the downstroke than endurance-based cycling (6) and the potential for faster acceleration. Although the time component associated with this improvement in acceleration is very small (perhaps several milliseconds), this may be crucial in short cycling events such as a track sprint race. Such exertions require cyclists to respond rapidly to tactical moves made by their opponents, in particular, the ability to find a position in the slipstream of the opponent.

Correlation analysis revealed that $\text{RCTD}_{\text{peak}}$ was significantly related to MA stiffness, with a moderate to strong correlation of $r = 0.61$ evident (Fig. 3A). When considering the MA stiffness methodology used in the current study, 37% of the variance in RCTD is attributable to quadriceps MA stiffness. This relationship was of greater magnitude than the correlation evident between RCTD and MIT (*r* = 0.52). This provides further indication that the role of MA stiffness in sprint cycling performance may be of equal or of greater importance to that of strength, and training programs should certainly consider developing this aspect of performance. The demonstration of improvements in stiffness after various types of specific training regimens (7,20,21,36) provides evidence that stiffness may be modified. In addition, it has been documented that chronic flexibility training can reduce musculotendinous stiffness (40). Therefore, given that stiffness is a modifiable neuromechanical property of the musculotendinous unit, coaches and athletes may consider applying certain training prescriptions to achieve an optimal level of stiffness for performance.

As evidenced by moderate ES, the tendency for elevated PO_{peak} and CT_{peak} in the SG compared with those in the CG also highlights the relationship between MA stiffness and sprint cycling. One of the primary objectives in training for sprint cycling is a high PO_{peak} and the ability to maintain this over the race distance (3). Along with the trend for a relationship between higher PO_{peak} in the SG, a significant moderate correlation was evident between MA stiffness and PO_{peak} during cycling (*r* = 0.43; Fig. 3D). Clearly, these improvements in power, CT, and CT profile are evidence of a significant relationship between MA stiffness and sprint cycling. Further research is required to determine whether an increase in MA stiffness after a specific training period influences sprint cycling performance and RCTD.

The information pertaining to MA stiffness and RCTD is particularly relevant when considering cadence and the associated time available for CT production during cycling. A cadence of 80 rpm results in the period for torque application during the downstroke to be approximately 300 ms. Higher cadences provide less time for torque application, meaning that RCTD is of primary concern as cadence rises. Accordingly, a relatively higher MA stiffness will be of greater benefit as cadence increases because of a faster RCTD. The cadence in the current study was fixed at 80 rpm; however, future research should examine the role of MA stiffness in RCTD across varying cadences.

It seems that higher stiffness values are ideal for rapid force production during the dynamic, concentric muscle actions of cycling, which is in congruence with other authors who have reported relationships between musculotendinous stiffness and isometric and concentric contractions (41). However, in many activities requiring the use of the stretch shortening cycle, there may be an upper limit to stiffness, beyond which the athlete is predisposed to an occurrence of soft tissue injury due to the inability to attenuate the applied forces (8,38,43). The potential relationship between stiffness and injury may not be as relevant for cycling because there are no high-level eccentric forces evident during the pedaling action. In contrast, during running or jumping, in particular, the landing phase, individuals are subjected to eccentric loads that may not be well attenuated by relatively stiffer individuals (38). Therefore, because MA stiffness seems to be integrally related to sprint cycling performance, it may be speculated for cyclists that the highest possible stiffness be attained to achieve maximum performance, without the associated inherent injury risks. This is unique to cycling owing to the repetitive, concentric-only muscular action.

The practical applications of this research are specifically directed toward cycling disciplines, where sprint efforts are undertaken under nonfatigued conditions such as sprint events in track cycling, e.g., 200-m and team sprints. In other track events, such as match sprinting, keirin, and scratch, a fast reaction to an opponent's move or attack is critical for performance. In these cases, a high RCTD may improve the initial acceleration response of the rider to respond quickly to tactical moves from other cyclists. In contrast, endurance cyclists are required to perform sprint efforts intermittently during a race while under conditions of metabolic and neuromuscular fatigue (23). Accordingly, further research might examine the influence of fatigue on MA stiffness and the ensuing effects on sprint cycling performance. Indeed other authors have reported that stiffness may be reduced under conditions of fatigue (19); however, the implications for performance in an activity such as road cycling are yet to be documented.

A strength of this article is the use of trained cyclists as participants. Although they were generally not sprint-trained cyclists, this is an important consideration because untrained cyclists may not have developed the muscular coordination during pedaling to permit stiffness to be a discriminatory factor when considering RCTD. One acknowledged limitation in the current study was that the measure of MA stiffness was limited to that of the quadriceps. During cycling, there are significant contributions from the musculature of the gluteals, quadriceps, hamstrings, gastrocnemius, soleus, and tibialis anterior (29), so the MA stiffness of each of these groups would certainly contribute to the overall performance output. However, the knee extensors are the most important contributors to the total power output while pedaling (13); therefore, the musculature of the quadriceps is the most relevant when examining the current hypothesis. Further, the use of a singular stiffness assessment load (50% of MIT) is a recognized limitation of the current study. In addition, the effect of anthropometric dimensions or bicycle dimensions on MA stiffness and RCTD was not examined in the current study. This limitation potentially reduces the applicability of the findings of this study because it is not yet clear whether these measures contribute to the apparent relationship between stiffness and RCTD. Further research in this area might consider the examination of such confounding factors.

Finally, previous research using other stiffness assessment procedures has normalized stiffness values using the slope of the linear stiffness–assessment torque relationship (22). Furthermore, muscle strength may be assessed independent of body size using various normalization techniques (18); however, to date, there is no consensus regarding the normalization of stiffness measurements. Stiffness normalized to strength (16,22) or body mass (5), along with nonnormalized stiffness (4,39,41) has been presented in the literature, and because there is indeed a relationship between body size and strength, a relationship between stiffness and body size or strength may exist. A final agreement on the issue of normalizing stiffness for body size or strength is beyond the scope of the current study; however, the formulation of a consensus statement about the normalization of stiffness values would be a worthwhile proposition for future research.

In conclusion, higher MA stiffness seems to be related to higher RCTD in trained cyclists during a single sprint effort. Relatively stiff cyclists also have a more effective CT profile when sprinting, with earlier CT_{peakA} and $RCTD_{peakA}$. Although MA stiffness level did not discriminate between PO_{peak} and CT_{peak}, the tendency for improvements in these variables suggests that higher MA stiffness is an integral component of sprint cycling.

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