Effects of Fatigue on Muscle Stiffness and Intermittent Sprinting during Cycling

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ABSTRACT

DITROILO, M., M. WATSFORD, E. FERNÁNDEZ-PEÑA, G. D'AMEN, F. LUCERTINI, and G. DE VITO. Effects of Fatigue on Muscle Stiffness and Intermittent Sprinting during Cycling. *Med. Sci. Sports Exerc.*, Vol. 43, No. 5, pp. 837–845, 2011. **Purpose**: It was recently demonstrated that musculoarticular (MA) stiffness is related to sprint cycling performance in nonfatigued conditions. This study examined whether relatively stiffer cyclists were more effective at sprinting under fatigued conditions, as occurs during endurance cycling competitions. **Methods**: MA stiffness of the quadriceps was assessed in 21 trained male cyclists (28.7 ± 9.5 yr, 1.74 ± 0.08 m, 67.5 ± 7.2 kg). Participants also performed a maximal 6-s sprint on a cycle ergometer to assess peak power output (PO_{peak}), peak crank torque (CT_{peak}), and peak rate of crank torque development ($RCTD_{peak}$). A cycling fatigue protocol then required cyclists to pedal at 30%, 35%, and 40% of PO_{peak} and sprint at the end of each stage. Surface EMG was recorded from vastus lateralis during each sprint and analyzed in the time domain as integrated EMG (iEMG) and in the frequency domain as instantaneous median frequency (MDF) adopting a continuous wavelet transform. Participants were then retested for MA stiffness. **Results**: MA stiffness (−12%) was significantly reduced after the cycling protocol. Further, PO_{peak}, CT_{peak}, $RCTD_{peak}$, and iEMG were reduced by 20%, 15%, 13%, and 20%, respectively, after the fatigue protocol ($P < 0.05$). When the cyclists were divided into relatively stiff (SG) and relatively compliant groups (CG), only SG exhibited significant decreases in MA stiffness, CT_{peak}, $RCTD_{peak}$ ($P < 0.05$), and instantaneous MDF ($R^2 = 0.705$). **Conclusions**: Whereas neuromechanical parameters were generally reduced under conditions of fatigue, stiff and compliant cyclists were affected differently, with the sprint abilities of SG decreased to the level of CG. It seems important for endurance cyclists to incorporate training strategies to maintain MA stiffness during competition to offset declines in sprint performance. **Key Words:** MUSCLE–TENDON UNIT, RATE OF CRANK TORQUE DEVELOPMENT, ELASTICITY, TRAINING, EMG

Road cycling performance is characterized by the rider being required to pedal at a submaximal level for most of the race, interspersed by high-intensity efforts. Such efforts are more likely to occur in the second half of the race and are generally related to tactical issues such as individual breakaways, the need to overcome hilly terrain, and to also be competitive in the final sprint (27). Although in road cycling the actual proportion of sprinting events represents a small portion of the whole race, these are often of pivotal importance. Cyclists need to be able to sprint in the last 200 m of the race, this potentially making the difference between winning and losing a race (1). Sprint cycling relies on the ability to produce high peak power output (PO_{peak}) and peak crank torque (CT_{peak}) (6,12). Along with the CT_{peak}, a high rate of crank torque development (RCTD) during cycling, which results in a greater impulse and initial force transmission capacity, is important for sprint performance. In addition, we have recently demonstrated that musculoarticular (MA) stiffness seems to be an important contributory factor for sprint cycling (33) because of its positive relationship with RCTD.

Stiffness, i.e., the ratio of the change in force to the change in muscle length, has been related to performance in many different sports. Specifically, higher stiffness has been related to elevated concentric and isometric muscular contraction capacity and especially to the rate of torque development (32,34). Such relationships are evident as higher stiffness conceivably improves the length–tension and force–velocity relationships within a muscle–tendon unit and may also improve the initial transmission of force (34). The same authors postulated that stiffness may be a relevant consideration when examining cycling because of the improvements in force transmission. Indeed, relatively stiffer cyclists exhibit superior crank torque development characteristics during sprinting when compared with more compliant ones (33).

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Such results were evident during a singular 6-s sprint undertaken in nonfatigued conditions. In road cycling, however, sprint efforts are mostly performed under fatigued conditions, although the fatigue level may vary considerably depending on the race duration, the variety of terrains, team tactics, and drafting (15).

Fatigue can be defined as an impairment in muscle performance, which manifests as a reduction in force and power generation. Such fatigue may be due to peripheral muscular changes but can also have a central origin (13) and has a variety of effects on different facets of physiological and mechanical function. For example, it has been previously demonstrated that fatigue induced by repeated muscular contractions can cause temporary changes in the stiffness properties of the muscle–tendon unit. Kubo et al. (19) reported that a repetitive isometric exercise was accompanied by a marked lengthening in electromechanical delay and an increase in tendon compliance. Further, in a group of well-trained runners, a reduction in both vertical and leg stiffness has been reported after a run test to exhaustion (7). In addition, fatigue caused by four periods of 30-s all-out sprint cycling exercise was demonstrated to lengthen electromechanical delay and reduce maximal isometric contraction and rate of force development in healthy men (36). Nonetheless, it must be recognized that the passive change in temperature alone has been solely shown to alter the stiffness characteristics of the tendon because of a rearrangement of the dense connective tissue. Specifically, muscle cooling would cause an increase (28), whereas a rise in temperature would be responsible for a reduction in muscle–tendon stiffness (24). In contrast, repetitive drop jumps did not change the elongation characteristics of the tendon and aponeurosis of the knee extensor muscles (18). Other authors did not find a significant postfatigue alteration of vertical stiffness measured by a hopping test in physically active male and female subjects (30).

It is clear that fatigue has noticeable effects on performance in a range of different tasks, and to the best of our knowledge, the effect of fatigue induced by a repetitive, concentric-only action such as cycling on the expression of MA stiffness is yet to be examined. Further, the relationship between initial MA stiffness levels and the response to fatigue is also an area of enquiry that is yet to be investigated. Accordingly, the aim of the present study was to investigate the effects of fatigue on lower body MA stiffness in trained cyclists and examine the resultant effects on their sprinting ability. On the basis of previous findings, it was hypothesized that fatigue would reduce MA stiffness, which would be associated with an impairment in intermittent sprint cycling performance. In addition, given the established relationship between stiffness and the force generating characteristics of human muscle, it was hypothesized that relatively stiffer participants would display a greater reduction in performance in neuromechanical properties resulting from fatigue. The outcomes of this study would provide empirical evidence to assist cycling coaches and conditioning coaches in the design of appropriate training programs to improve cycling performance.

METHODS

Participants

Twenty-one trained male competitive endurance cyclists (28.7 ± 9.5 yr, 1.74 ± 0.08 m, 67.5 ± 7.2 kg) volunteered to participate in this project. The inclusion criteria were a minimum of 4 yr of cycling experience and 250 km of training per week. The cyclists participated in 409 ± 212 km of training per week during 5.5 ± 1.8 training sessions. The sample was experienced, with an average of 11.8 ± 8.0 yr of cycling involvement across the group. Participants with a range of cycling ability were recruited, ranging from masters level (n = 6), to under-23 elite (n = 10), to professional (n = 3). The group also included two triathletes who had previously been involved in competitive cycling.

Participants arrived at the laboratory in a rested state, having been asked to maintain a normal diet and 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 lower body or reported other health issues that affected performance. Before their involvement, all participants provided written informed consent, and the research was approved by the ethics committee at the University of Urbino, Italy.

Testing Procedures

Unilateral quadriceps maximal isometric torque and MA stiffness were assessed in all participants. This muscle group was selected because it represents the primary source of crank torque production during the downstroke of cycling (29). After the assessment of these mechanical variables, the participants were required to complete a cycling protocol on a bicycle ergometer that was designed to elicit muscular fatigue of the lower body. For this purpose, three separate 3-min cycling bouts were performed, each followed by a 6-s sprint. Crank torque variables were assessed during each of these sprints to determine the effects of fatigue, specifically PO_{peak}, CT_{peak}, $RCTD_{peak}$, and the angles at which CT_{peak} and $RCTD_{peak}$ occurred were assessed. After the final sprint effort MA stiffness was reassessed. An overview of the testing procedures is provided in Figure 1. For analytical purposes, the cyclists were divided into two subgroups according to their quadriceps MA stiffness characteristics. One group included the stiffest cyclists (SG) and the other group contained the more compliant cyclists (CG). Mechanical variables and sprint cycling ability were then compared between the two groups at baseline and under conditions of fatigue.

Warm-up

A standard warm-up was used and replicated for the tests on the leg extension machine and the cycle ergometer. This

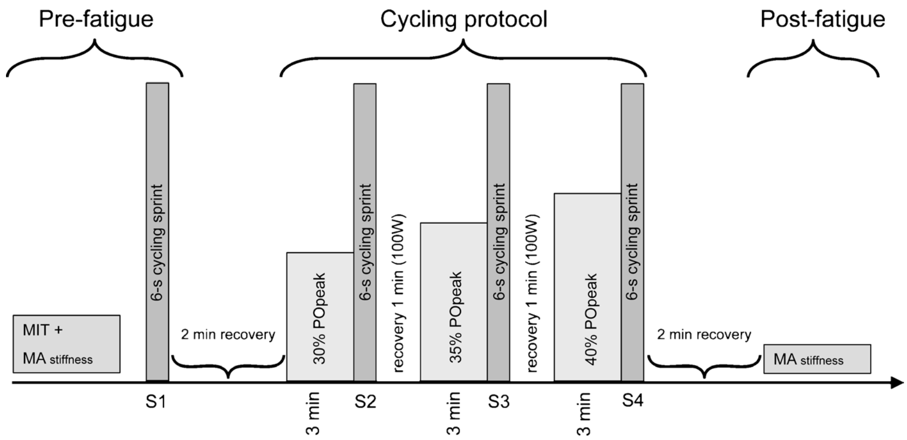

FIGURE 1—Schematic representation of the research design. MA stiffness indicates musculoarticular stiffness; MIT, maximal isometric torque; S, sprint; PO_{peak}, peak power output.

consisted of 3 min of cycling at 100 and 150 W for a further 3 min. After the isometric muscle function tests, a further 6 min of cycling at 150 W was allowed to prepare the participants for cycling.

Isometric Force

Before the cycling protocol, a unilateral maximal isometric test of the knee extensor musculature was performed on a seated leg extension dynamometer (Technogym, Gambettola (Fo), Italy). This test was performed on the participant's preferred leg, which was defined as the leg that they favored for performing powerful movements. The participant sat in the seat with a hip flexion angle of 90° and knee flexion angle of 100° (where 180° represents full extension). This position was adopted as a 100° knee angle has been associated with the optimal angle for force production (22), and this angle also coincides with the production of CT_{peak} and $RCTD_{peak}$ when cycling (33). The lateral femoral condyle was aligned with the axis of the dynamometer. 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 attempted to extend the lower leg. Participants were fastened to the device using straps to minimize the potential for gluteal contraction and resultant hip extension during the test. After familiarization with the device, participants were instructed to maximally produce force with the quadriceps, as quickly as possible, for approximately 4 s. Strong verbal encouragement was given to each participant. Arms were held across the chest to prevent any contribution from the upper body. Two trials were conducted for each participant, with the best result used to determine the load with which MA stiffness was assessed. Two minutes of passive rest was permitted between trials.

Force data were collected by a load cell (Leane International, Parma, Italy; measurement range = 0–750 kg, output = 2.92 $mV \cdot V^{-1}$) that was positioned in series with the plane of force application for the leg extension test. Data were sampled at a rate of 10 kHz. 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 low-pass–filtered using a third-order, zero-phase Butterworth filter at a 300-Hz cutoff frequency. Before data analysis, the load cell signal was filtered using a 5-ms moving average.

MA Stiffness

Lower body MA stiffness was assessed using a free oscillation technique. This method of stiffness assessment has been previously highlighted as valid and reliable (14,25,32). This 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 complex (25,31). Further detail about the theoretical elements of stiffness quantification is available elsewhere (25,31,32).

Unilateral (preferred leg) quadriceps MA stiffness assessment was performed on the leg extension dynamometer before and after the cycling fatiguing protocol. Participants were seated in an identical position to that used for the isometric force assessment, with the knee flexed at an angle of 100°. A single assessment load corresponding to 50% of maximal isometric force was used to quantify submaximal MA stiffness, which the participants supported on the distal portion of the anterior lower leg. The same assessment load was used at the pretest and posttest conditions. Participants were required to support the assessment load, and a perturbation of 100–150 N (34) was applied to the support bar at the distal lower limb. The ensuing oscillations were recorded by a uniaxial accelerometer (Crossbow, Milpitas, CA) attached to the distal end of the lever arm of the dynamometer. This assessment method was largely based on the work of Granata et al. (14), although there were some subtle differences surrounding setup position and load in the current study as described by Watsford et al. (33).

Owing to a possible link between MA stiffness and strength or body size, stiffness data have previously been normalized using either the assessment load (21) or the body size (5). However, owing to a lack of consensus regarding the need to normalize stiffness data, stiffness was not normalized in the current study; rather, the raw result was analyzed.

Accelerometer data were sampled at 1000 Hz and recorded to a personal computer using a 16-bit A/D converter. Two stiffness assessment trials were completed for each participant, separated by a 1-min rest period, with the results from these trials averaged for analysis. A Butterworth low-pass filter (third order) with a cutoff frequency of 6 Hz was used for data filtering. As per the method of McNair et al. (25) who examined hamstring stiffness using a free oscillation technique, the length of the lever arm was used to transform linear into rotational stiffness. The excellent reliability of the current test of quadriceps stiffness was reported by Watsford et al. (33).

Sprint Cycling Performance

Peak power output. To quantify the PO_{peak} of each participant, a 6-s sprint cycling exercise (S1) was performed by each participant on an SRM ergometer (Schoberer Rad Meßtechnik GmbH, Jülich, Germany). The ergometer was set to isokinetic mode, with cadence fixed at 80 rpm. The SRM crank set, equipped with strain gauges, directly measured the torque generated by the force applied to the pedals perpendicularly to the crank length. The participant's own bicycle measurements were used to customize the ergometer, and participants used their own pedals on the ergometer; thus, the assessment conditions replicated normal bike setup as best as possible.

Before the maximal sprint, the participants were required to pedal at a low intensity (50–100 W) at 80 rpm 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, separated by 3 min of recovery. The test that 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 (9).

Peak crank torque and rate of crank torque development. The five pedal revolutions exhibiting the highest power output during the 6-s sprint were chosen for analysis of CT variables, which were averaged during the five revolutions. CT_{peak} was the highest value recorded from the CT data during the downstroke, and instantaneous $RCTD_{peak}$ was calculated as the highest rate of change in the CT values for each downstroke of the selected leg. To gain further insight into the dynamics of the CT profile, the angles at CT_{peak} and at $RCTD_{peak}$ were assessed. The assessment of these critical points on the torque profile was important in determining any temporal shifts in torque generation characteristics.

Cycling fatigue protocol. To examine the effects of fatigue on MA stiffness and cycling performance, a protocol was designed to induce muscular fatigue. The primary variable for consideration was PO_{peak}, given that this is a primary consideration in cycling performance (8). The cyclists were required to pedal for three stages, each lasting 3 min, at a cadence of 80 rpm. The intensity of each stage was set at 30%, 35%, and 40% of PO_{peak}, respectively. At the end of each stage, a 6-s sprint was performed as previously described (S2, S3, and S4, respectively). As depicted in Figure 1, 1 min of active recovery was allowed, during which the cyclist pedaled at 100 W. After the 1-min recovery, the participants immediately commenced the subsequent stage of the protocol. This protocol was developed after pilot testing, with the sole purpose of inducing muscular fatigue of the lower limbs. Each of the mechanical parameters previously described for the cycling sprint performance were measured during each of the sprints in the cycling exercise. After the completion of the final sprint of the final stage, participants were permitted 2 min of recovery and then repeated the MA stiffness test.

EMG. Surface electrical activity (EMG) of vastus lateralis (VL) was also measured during the cycling sprints, in rested (S1) and fatigued conditions (S2, S3, and S4). Skin was shaved, slightly abraded with sandpaper, and cleaned with alcohol. This ensured low impedance at the skin–electrode interface ($Z < 5$ kΩ). Ag/AgCl bipolar electrodes (Blue Sensor N-00-S; Ambu Medicotest A/S, Ølstykke, Denmark) were placed over the muscle belly of the selected muscle at an interelectrode distance of 20 mm. To avoid artifacts from lower limb movements, the wires connecting electrodes were well secured with tape. The signal was amplified at a gain of 600, and common mode rejection rate and input impedance were 95 dB and 10 GΩ, respectively. EMG data were online band-pass–filtered (10–350 Hz) using a fourth-order Butterworth filter. The signal was sampled at 1000 Hz and stored on a PC using a 16-bit A/D converter data acquisition system (APLabDAQ; APLab).

Raw EMG data were full wave–rectified and integrated (iEMG) over each pedal stroke. For each sprint, the iEMG values were then averaged during the five revolutions with the highest power outputs as previously mentioned for the other CT variables. Furthermore, time–frequency analysis (continuous wavelet transform) was performed to analyze the time-dependent frequency content of each 6-s epoch of the raw EMG data. The scalogram was calculated as the square of the continuous wavelet transform estimated using the Morlet waveform as described by Karlsson et al. (16). The continuous wavelet transform has been shown to provide more accurate and precise estimates of spectral variables than other time–frequency methods when analyzing nonstationary EMG signals (16). Within each 6-s sprint,

TABLE 1. Mean values (SD) of the anthropometric and training characteristics of the two groups.

	Age (yr)	Height (cm)	Body Mass (kg)	Years of Training	Training Sessions		Cyclists Included
					Number per Week	Kilometers per Week	
CG (n = 10)	27.4 (9.5)	173.7 (5.8)	66.6 (7.6)	10.3 (5.7)	5.2 (1.8)	412 (220)	4 M, 3 E, 2 Pr, 1 Tr
SG (n = 10)	28.3 (8.7)	174.7 (10.1)	68.1 (7.4)	13.1 (8.5)	5.9 (1.8)	417 (222)	2 M, 5 E, 2 Pr, 1 Tr

E indicates under-23 and elite; M, masters level; Pr, professional; Tr, triathlete.

eight bursts of electrical activity were identified between 337° and 134° of each revolution, corresponding to the period when VL is most active (29). The instantaneous median frequency (MDF) was then calculated for each burst of activity from the scalogram of the EMG signal between 337° and 134°. The duration of each burst of activity was approximately 330 ms, corresponding to a fixed pedaling frequency of 80 rpm. The data analysis was performed using MATLAB 7.9 (The MathWorks, Cambridge, UK).

Statistical Analysis

Before data analysis, all variables where checked for normality (Shapiro–Wilk test) and homoscedasticity of variance (Levene test) and logarithmically transformed when necessary (MA stiffness). Data are expressed as mean ± SD, unless otherwise stated. Initially, the whole sample was analyzed with a view to examine the effectiveness of the fatiguing protocol. A paired-samples Student's t-test was used to detect the effect of fatigue on MA stiffness, and a one-way ANOVA with repeated measures was used to examine the effect of fatigue on cycling variables that encapsulated power, crank torque parameters, and iEMG data.

Further, the participants were divided into two groups using a median split technique. Participants were ranked according to their MA stiffness value and distributed to either the SG, which included the 10 participants exhibiting the highest stiffness values, or the CG, which included the 10 participants displaying the lowest stiffness. The median value was discharged from the between-group comparisons. The anthropometric and training characteristics of the two groups are outlined in Table 1, which show a substantial level of homogeneity between groups.

The projected sample size was calculated ensuring a statistical power of 0.80, a two-tailed α of 0.05 and estimating an effect size of 0.60 between the prefatigue and the postfatigue condition (n required = 18) and 0.75 between SG and CG (n required = 10 for each group) for the primary dependent variables.

The PO_{peak} obtained during S1 was set to 100% to enable the PO_{peak} obtained during the fatiguing protocol to be expressed as a percentage. To analyze whether fatigue affected the SG and CG differently, the following statistical analyses were performed: a 2 (group; SG and CG) × 2 (test condition; prefatigue and postfatigue) ANOVA with repeated measures on the last factor was computed to analyze the change in MA stiffness; 6 (PO_{peak}, CT_{peak}, $RCTD_{peak}$, angles at CT_{peak} and at $RCTD_{peak}$, and iEMG) separate 2 (group; SG and CG) × 4 (S1, S2, S3, and S4) two-way ANOVA with repeated measures on the last factor were used to analyze the cycling variables. When a significant F value was achieved, a Tukey *post hoc* test was used to examine where significant differences occurred.

Instantaneous MDF was analyzed by taking the average of each burst of electrical activity over the whole group of cyclists, the CG, and the SG and plotting it versus time (i.e., the sequence of the 32 bursts). A linear regression equation was determined along with the coefficient of determination (R^2).

All statistical analyses were conducted using the Statistica software (release 8.0; Statsoft Italia, Vigonza, Italy). An α level of $P < 0.05$ was considered statistically significant for all comparisons.

RESULTS

With reference to the whole group, MA stiffness was significantly reduced by 12% as a result of the fatigue protocol (1860.7 ± 698.8 vs 1634.1 ± 661.7 $N \cdot m \cdot rad^{-1}$, F = 12.00, $P < 0.05$). When considering the two groups separately, MA stiffness was significantly reduced in SG as a result of fatigue (2367.8 ± 691.6 vs 1946.6 ± 701.4 $N \cdot m \cdot rad^{-1}$, F = 7.29, $P < 0.05$), whereas that in CG was not affected (1367.6 ± 186.9 vs 1314.3 ± 328.8 $N \cdot m \cdot rad^{-1}$, P = 0.56). When a prefatigue comparison between the groups was performed, the SG showed a significantly higher MA stiffness score than CG ($P < 0.05$); however, this difference was lost in postfatigue comparison despite the presence of a trend.

The cycling protocol was effective in inducing a significant reduction in PO_{peak} (Table 2). A 7% decrement per stage was evident, and in total, a 20% reduction in PO_{peak}

TABLE 2. Mean values (SD) of cycling and electromyography variables for all participants measured across the fatigue protocol (n = 21).

	PO_{peak} (W)	CT_{peak} (N·m)	CT_{peak} Angle (°)	$RCTD_{peak}$ ($N \cdot m \cdot s^{-1}$)	$RCTD_{peak}$ Angle (°)	iEMG (mV)
S1	795.9 (104.5)	144.4 (21.3)	99.9 (8.7)	1301.8 (230.4)	43.2 (5.8)	67.6 (15.5)
S2	742.9 (102.0)	138.7 (21.0)	102.1 (7.5)	1229.7 (248.0)	44.7 (6.7)	61.0 (14.1)*
S3	693.5 (117.2)*	131.4 (23.4)*	102.0 (6.7)	1173.3 (161.0)*	46.0 (6.9)	59.1 (16.9)*
S4	641.1 (107.0)*	123.3 (20.5)*	103.8 (7.5)*	1139.3 (181.4)*	47.3 (7.4)*	54.4 (16.1)*

* Significantly different from S1, $P < 0.05$.
S1 indicates sprint in rested condition; S2, S3, S4, sprints in fatigued condition.

was observed at the completion of the fatiguing protocol. When considering the two-way ANOVA analysis, only the "fatigue" factor exhibited significant differences ($F = 27.60$, $P < 0.01$), whereas no significant differences were documented for the "group" factor (with PO_{peak} being 773.0 vs 823.8 W at S1 and 639.1 and 643.7 W at S4 for CG and SG, respectively, $F = 0.23$, $P = 0.64$), or the interaction ("group" × "fatigue," $F = 0.87$, $P = 0.46$), thus suggesting that the two groups were fatigued to the same extent.

As for EMG parameters, iEMG was significantly reduced during the cycling fatigue protocol (Table 2) when compared with S1 ($F = 16.58$, $P < 0.01$). The instantaneous MDF was reduced on average by 0.141 Hz per revolution ($R^2 = 0.342$; Fig. 2A).

When EMG data were analyzed separating the two groups (CG and SG), it was noticed that the SG demonstrated a more prominent decline both in iEMG and instantaneous MDF values during the fatiguing protocol. In particular, although significantly different in both groups ($F = 13.16$, $P < 0.01$), the SG displayed a 22% reduction in iEMG (from 69.5 to 54.1 mV) versus a 16% reduction in the CG (from 64.6 to 53.9 mV). In contrast, instantaneous MDF decreased by 0.374 Hz per revolution only in the SG ($R^2 = 0.705$), whereas in CG, there was no significant reduction during the four sprints ($R^2 = 0.001$; Fig. 2B).

The CT_{peak} and angle at CT_{peak} are presented in Figure 3 and Table 2. In the whole group of cyclists, the CT_{peak} was

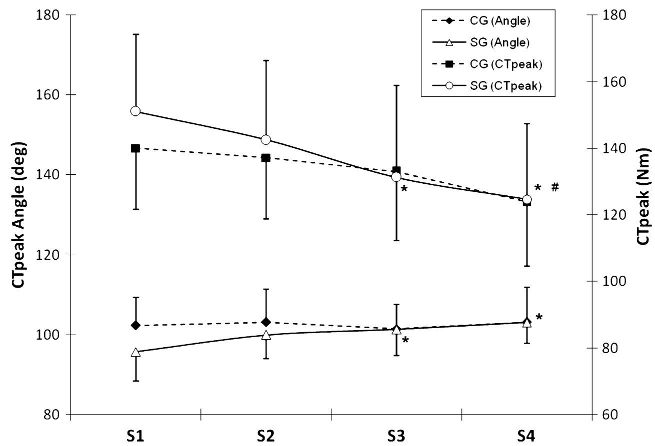

FIGURE 3—Mean values (±SD) of peak crank torque (CT_{peak}) and angle at CT_{peak} in the relatively stiff (SG) and compliant groups (CG) across the four cycling sprints (S1, S2, S3, and S4). *Significantly different from S1 ($P < 0.05$). #Significantly different from S2 ($P < 0.05$).

reduced by 15% overall ($F = 14.36$, $P < 0.01$) when considering the changes from S1 to S4, and the angle at CT_{peak} was significantly increased by 4° after the fatiguing protocol ($F = 2.98$, $P < 0.05$; Table 2). When the CG and SG were analyzed separately (Fig. 3), a significant main effect for testing condition was detected for CT_{peak} and angle at CT_{peak} ($F = 13.57$ and $F = 3.56$, respectively, $P < 0.05$) along with a significant interaction between the factors for angle at CT_{peak} ($F = 3.05$, $P < 0.05$). The *post hoc* test demonstrated a significant reduction in CT_{peak} ($P < 0.05$) and increase in angle at CT_{peak} ($P < 0.05$) across the fatiguing protocol; however, this result was isolated to the SG.

The results for $RCTD_{peak}$ and angle at $RCTD_{peak}$ are depicted in Table 2 (whole group) and in Figure 4 (CG and SG). When considering the whole group of cyclists, $RCTD_{peak}$ displayed a significant reduction (by 13%; $F = 7.82$, $P < 0.01$) after the fatiguing protocol, whereas angle at $RCTD_{peak}$ was increased by 4° ($F = 5.56$, $P < 0.01$;

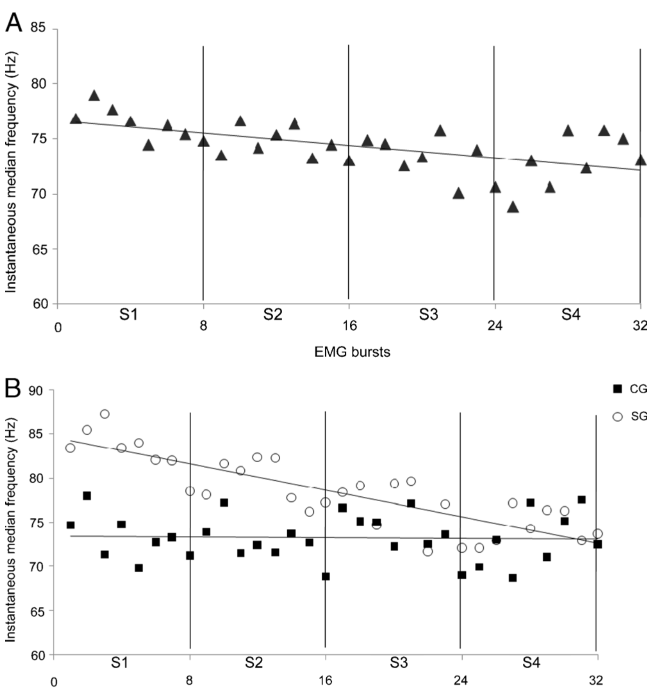

FIGURE 2—Instantaneous MDF calculated using the continuous wavelet transform of the VL EMG signal. Data are presented as the average over the whole group of cyclists (A) and in the stiff (SG) and compliant groups (CG) (B) across the 32 bursts of electrical activity recorded during the four cycling sprints (S1, S2, S3, and S4). Linear regression equations: $y = -0.141x + 76.65$, $R^2 = 0.342$ (A); $y = -0.009x + 74.42$, $R^2 = 0.001$ (B; CG); $y = -0.374x + 84.61$, $R^2 = 0.705$ (B; SG).

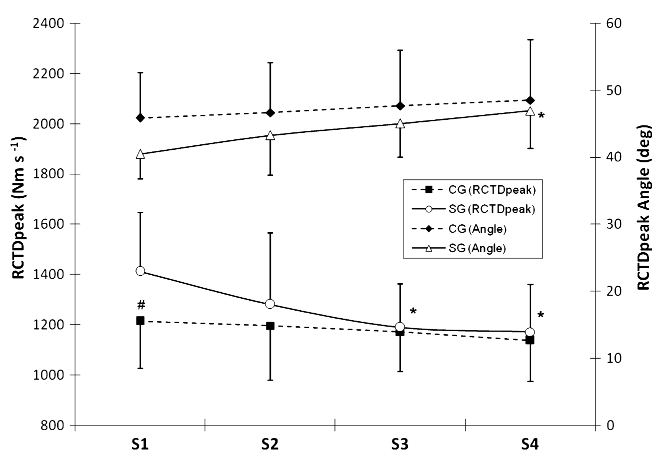

FIGURE 4—Mean values (±SD) of rate of peak crank torque development ($RCTD_{peak}$) and angle at $RCTD_{peak}$ in the relatively stiff (SG) and relatively compliant groups (CG) across the four cycling sprints (S1, S2, S3, and S4). *Significantly different from S1 ($P < 0.05$). #Significantly different from SG ($P < 0.05$).

Fig. 4). When CG and SG were analyzed separately (Fig. 4), a significant main effect for testing condition was observed for $RCTD_{peak}$ ($F = 7.65$, $P < 0.05$) and angle at $RCTD_{peak}$ ($F = 6.44$, $P < 0.01$), along with a significant interaction between the factors for $RCTD_{peak}$ ($F = 2.97$, $P < 0.05$). The *post hoc* test demonstrated a significant reduction in $RCTD_{peak}$ ($P < 0.05$) and increase in angle at $RCTD_{peak}$ ($P < 0.05$) for the SG only when comparing the data from S1 to S4.

DISCUSSION

The main finding of this investigation was that fatigue generated from a cyclic, concentric-only muscular contraction was associated with a reduction in MA stiffness. Moreover, relatively stiffer cyclists exhibited a larger decline and actually regressed to the level of the compliant cyclists for MA stiffness and other neuromechanical parameters. Regardless of the duration, the current cycling fatiguing protocol proved to be valid, as the PO_{peak}, one of the most important factors affecting cycling performance (8), was significantly decreased by 20% overall. Interestingly, both the CG and SG displayed significant reductions. Furthermore, an alteration in the surface EMG parameters, suggestive of neuromuscular fatigue (17,26), was also demonstrated because of the fatiguing protocol.

Effects of fatigue on MA stiffness. Research examining the effect of fatigue on stiffness has used a variety of exercises to elicit fatigue in the muscle–tendon unit. To date, no studies have used a repeated, concentric-only exercise such as cycling to evoke fatigue; thus, the results of this study provide an alternate insight into changes in MA stiffness characteristics. A 12% reduction in MA stiffness after the cycling exercise was evident in the present study for the whole group of cyclists. Kubo et al. (20) reported a significant reduction in tendon stiffness of approximately 27% after a series of either maximal or submaximal isometric contractions.

Within the muscle–tendon complex, it has been previously explained that the muscle stiffness increases linearly with increasing muscle tension (11,31). It can be therefore postulated that the same mechanisms that impair muscle contractility in fatiguing conditions will contribute to reduce muscle stiffness as well. How any alteration of tendon stiffness could affect MA stiffness is more complicated to explain, as it is independent of the contractile component (11). Kubo et al. (18) suggested that repeated isometric contractions lead to an increase in tendon compliance as a result of static creep. Further, an increase in temperature of the connective tissue is considered as a viable mechanism to alter the viscoelastic properties of tendon (20). Clearly, the mechanisms underlying changes in tendon stiffness, and indeed MA stiffness resulting from multiple concentric contractions remain to be clarified.

Interestingly, when the CG and SG were analyzed separately, a significant decrease in MA stiffness after the fatiguing exercise was evident only in the SG. Initially, the SG displayed significantly higher MA stiffness; therefore, this reduction in the SG was a regression toward the level of the CG. This reduction was mirrored by a significant reduction in instantaneous MDF, which was evident in the SG but not in the CG despite both groups demonstrating reduced PO_{peak} and iEMG after the fatiguing protocol. MA stiffness is positively related to concentric rate of force development (34) and $RCTD_{peak}$ (33), and given this relationship, it is plausible that the participants in the SG possessed a higher percentage of type II muscle fibers than the CG. A positive relationship between rate of force development and percentage of fast-twitch fibers has indeed been previously demonstrated (3). Also, muscles with a higher composition of fast twitch fibers have been related to higher muscle stiffness (4,10) but not tendon stiffness (10). Furthermore, Komi and Tesch (17) observed that fatigue-induced responses in the surface EMG parameters were related to the individuals' muscle fiber type composition. In fact, a decline in EMG amplitude was demonstrated in individuals whose muscles (VL) were characterized by a high percentage of fast-twitch fibers; however, such a response was not evident in those with a higher percentage of slow-twitch fibers. It was also reported that the mean frequency of the EMG power spectrum decreased only in individuals with a high percentage of fast-twitch fibers. In the present study, we did not measure muscle fiber composition; however, EMG parameters do provide some evidence to explain the current findings. Specifically, it seems that iEMG was reduced at a higher rate in the SG compared with the CG, and instantaneous MDF was reduced only in the SG. Certainly, a more detailed examination, inclusive of muscle fiber type, is recommended for future research.

Effects of fatigue on cycling variables. CT_{peak} and $RCTD_{peak}$ were reduced by 15% and 13%, respectively, after the fatiguing task, mirrored by the 20% reduction in PO_{peak}. Angle at CT_{peak} and at $RCTD_{peak}$ occurred significantly later in the crank cycle (by approximately 4°) after the fatiguing task, indicating a rightward shift in the torque profile. To the best of our knowledge, this is the first time that the effect of fatigue on these parameters has been analyzed, and such a finding would certainly affect performance under fatigued conditions. Issues surrounding peripheral fatigue may have reduced the expression of lower body force production resulting in decreased CT_{peak}. Further, neural modifications may have altered the $RCTD_{peak}$. An increase in angle at CT_{peak} and at $RCTD_{peak}$ implies a delay in peak torque generation. It was previously demonstrated that stiffer cyclists, in rested conditions, reached CT_{peak} and $RCTD_{peak}$ earlier in the crank cycle compared with more compliant ones (33), thus potentially increasing the ability of the rider to accelerate the bike in response to an opponent's tactical move. However, such a result is mainly beneficial in track cycling where the riders are required to sprint by dramatically increasing their velocity in a very short time.

In road cycling, because the average velocity of the final stages of a race is already relatively high, and the PO_{peak} reached is considerably lower than that of track cycling, the magnitude of acceleration required to sprint is significantly lower (23). Thus, even though statistically significant, it is unlikely that a rightward shift of the torque profile by 4° under fatigued conditions would affect torque application in an applied setting such as a sprint during an endurance road race. In contrast to the results of the SG, it seems that neither CT_{peak} nor $RCTD_{peak}$ is affected in more compliant individuals under fatigued conditions. However, as more compliant cyclists tend to originate from a lower starting point, there may be negative connotations for sprinting under nonfatigued conditions for relatively compliant cyclists.

There are important implications to arise from these results. It is important to develop training programs that can maintain the expression of MA stiffness under conditions of fatigue because this will have direct positive consequences for intermittent sprinting during endurance cycling events. The specific training drills required for such a purpose may include, but not be limited to, plyometric-style activities or other forms of strength training, e.g., Yamamoto et al. (35). In this regard, it was demonstrated that when explosive strength training was introduced to replace a portion of endurance training in cyclists, this prevented a decrease in mean power output during a 30-s cycle ergometer test without compromising endurance performance (2). However, further research is required to investigate the short-term and long-term effects of strength training on stiffness under conditions of fatigue.

Given that endurance-trained cyclists were used as participants in the current study, their training experience and weekly volume ensures that the results and practical applications of this study are directly applicable to other groups of well-trained cyclists. The primary limitation affecting the results is the type of cycling protocol used to induce fatigue, in that it was not necessarily identical to the type of fatigue witnessed during road-race conditions. For example, fatigue resulting from up to 4 h of cycling could perhaps be related to more central or neurological mechanisms and is quite different from the type of fatigue induced by approximately 9 min of intense pedaling, which is probably more related to metabolic or peripheral fatigue. Further, the absence of muscle fiber type measurement, along with the independent contribution of muscle and tendon stiffness to the overall MA stiffness, was a clear shortcoming of this investigation. However, the current battery of assessments does provide substantial evidence to support a relationship between changes in MA stiffness induced by fatigue, along with ensuing changes in intermittent sprinting during cycling, although a similar style of study with a larger cohort would be valuable and would improve the statistical power.

CONCLUSIONS

This is the first study to assess the effect of fatigue induced by a concentric cycling exercise on MA stiffness and other mechanical parameters and the first to demonstrate that fatigue affects relatively stiff and compliant cyclists differently. The salient findings are as follows: 1) a fatiguing cycling protocol invoked a reduction in quadriceps MA stiffness; 2) these changes in neuromuscular properties coincided with reductions in PO_{peak}, CT_{peak}, and $RCTD_{peak}$ measured with a cycle ergometer; and 3) the torque producing characteristics of relatively stiffer cyclists seem to be significantly affected by fatigue, insomuch as their torque producing characteristics when sprinting were decreased to the level of compliant ones. This reduction in performance was also observed in the alteration of the surface EMG parameters. It seems that when the aim is to sprint in nonfatigued conditions, it is worthwhile to train quadriceps MA stiffness to improve sprint efficiency. Conversely, because MA stiffness seems to reduce under conditions of fatigue and is associated with a reduction in performance, it seems important for endurance cyclists to develop training modalities that maintain stiffness during the course of endurance events. Such maintenance may enhance sprint performance under conditions of fatigue.

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APPLIED SCIENCES

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