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Muscle Architecture and Optimum Angle of the Knee Flexors and Extensors: A Comparison Between Cyclists and Australian Rules Football Players

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Abstract

Brughelli, M, Cronin, J, and Nosaka, K. Muscle architecture and optimum angle of the knee flexors and extensors: a comparison between cyclists and Australian Rules football players. *J Strength Cond Res* 24(3): 717–721, 2010—The purpose of this study was to investigate differences in optimum angle of peak torque (knee extensors and flexors) and muscle architecture (vastus lateralis) between 9 cyclists and 9 Australian Rules football (ARF) players. The angles of peak torque of the ARF players were significantly ($p < 0.05$) greater during knee extension (70.8 ± 3.5 vs. 66.6 ± 5.9°) and smaller during knee flexion (26.2 ± 2.9 vs. 32.3 ± 3.8°) compared with the cyclists. The ARF players had significantly ($p < 0.05$) smaller pennation angles (19.3 ± 2.0 vs. 24.9 ± 2.5°) and longer fascicle lengths (7.9 ± 0.7 vs. 6.2 ± 0.8 cm) in comparison with the cyclists. There were no significant differences between groups regarding muscle thickness or peak torque ratios between the quadriceps and hamstrings. Muscle architectural changes associated with resistance strength training need to be investigated so that the effects of training on architecture and functional performance can be determined.

Key Words fascicle length, pennation angle, optimum length, quadriceps:hamstrings ratio, muscle thickness

Introduction

Muscle architecture and the optimum angle of torque development have important roles in skeletal muscle function. Several studies have reported alterations in pennation angle, fascicle length, length-tension, and torque-angle curves after acute and chronic resistance training (for a recent review, see Brughelli and Cronin [13]). It seems that both contraction mode (e.g., eccentric vs. concentric contractions) and muscle length (e.g., short vs. long lengths) influence these alterations (11,22,23). It is conceivable that athletes who repeat specific movement patterns consisting of similar contraction modes and muscle lengths will have similar muscle architecture and length-tension profiles. For example, during the pushing phase of cycling, the hip joint is predominantly held in a flexed position and the knee joint is repeatedly extended. Because the rectus femoris (RF) crosses both the hip and knee joints (origin at the anterior inferior iliac spine and ilium, superior to the acetabulum, and inserts into the patella and tibial tubercle), it contributes to the kinematics of hip flexion and knee extension. Thus, the active excursions (i.e., changes in muscle fiber lengths) of the RF are different during cycling in comparison with the running movement (25,27). In other words, the RF is contracting at shorter muscle fiber lengths during cycling.

It has been speculated that the angle of peak torque can be altered with specific functional/sport training, such as cycling (predominantly concentric training at short muscle fiber lengths) and running/sprinting (both eccentric and concentric training at optimum or near-optimum muscle fiber lengths) (15). The studies that have investigated the effects of previous sports training on torque-angle development have used predominantly endurance athletes (i.e., cyclists and long-distance runners) (15,25,27). Herzog et al. (15) and Savelberg and Meijer (25) have reported that long-distance runners were stronger at longer muscle fiber lengths and that cyclists were stronger at shorter muscle fiber lengths. Conversely, Ullrich and Brueggemann (27) have reported that cyclists did not produce peak torque at significantly different joint angles in comparison with tennis players, endurance runners, or triathletes. The effects of a mixture of training methods (i.e., endurance and sprinting training), used in sports such as Australian Rules football (ARF), on the torque–angle of peak torque relationship, are not known. In ARF, players regularly perform movements in which the

lower-limb muscles contract eccentrically at long muscle fiber lengths, which include kicking in place, kicking while running, maximum velocity sprinting, accelerating, change of direction, jumping, and landing (5,26,28). In addition, ARF players perform intensive endurance training because they often are required to cover a total distance of more than 15 km in a single game (14). Because such sports require great levels of strength, power, and cardiovascular and muscular endurance, it would be interesting to know whether the optimum angle of peak torque adapts to shorter or longer muscle fiber lengths.

None of the previously mentioned cross-sectional studies have investigated the optimum angle of the knee flexors (i.e., hamstrings) or peak torque ratios between the quadriceps and hamstrings (Q/H ratios). The hamstrings have important roles in maintaining pelvic stability, controlling the transfer of power between hip and knee joints, controlling rotation/translation mechanisms during running and jumping, and aiding in hip extension (9,16,17,21). In addition, the optimum angle has been related to hamstring injury risk and injury rates. Thus, the optimum angles of both the knee flexors and knee extensors are of interest to the authors.

Muscle architecture (i.e., muscle thickness, pennation angle, and fascicle length) plays an important role in athletic performance because pennation angle and fascicle length are thought to influence force production and muscle shortening velocity (2,3,18). Recent studies have reported increases in fascicle length (vastus lateralis [VL]) after power and eccentric training (4,6,7). Because elite sprinters have been shown to have longer fascicle lengths than nonelite sprinters, an increase in fascicle length is thought to have favorable implications for sprint and jump performance (2,20). It has been proposed that longer fascicle lengths could enhance sprint performance because of greater maximal shortening velocities, which would ultimately increase power production (20). However, information on sport-related differences in pennation angle and fascicle length is limited. No previous studies, to our knowledge, have compared fascicle lengths or pennation angles between athletes who perform predominantly concentric muscle contractions at short muscle fiber lengths (e.g., cyclists) and athletes who perform a mixture of explosive training, sprint training, and endurance training (e.g., ARF players). Once more, it would be of interest to ascertain whether the fascicle lengths and pennation angles of athletes who use a mixture of endurance and explosive training adapt in any manner. The purposes of this study were to 1) compare the angles of peak torque (knee extensors and knee extensors) of cyclists and ARF players and 2) compare the muscle architecture of cyclists and ARF players.

METHODS

Experimental Approach to the Problem

To answer the stated purposes of this paper, the optimum angle of peak torque during knee flexion and knee extension in cyclists and ARF players were measured using an isokinetic dynamometer. In addition, ultrasound was used to compare pennation angle, fascicle length, and muscle thickness between groups. Independent t-tests were used to determine whether the 2 groups differed significantly in the variables of interest. The researchers hypothesized that the 2 groups would show different profiles for optimum angle and muscle architecture, which may be attributable to either specific long-term training or genetic differences.

Subjects

Nine male endurance cyclists (age 26.5 ± 2.5 years; height 180.3 ± 12.4 cm; weight 79.5 ± 6.4 kg) and 9 male ARF players (age 24.9 ± 3.2 years; height 183.5 ± 11.5 cm; weight 83.3 ± 5.3 kg) participated in this study. The inclusion criterion for all athletes was at least 3 years of training in their respective sports. All subjects were club sport athletes and were not elite or professional (i.e., convenience sample). The measurements were taken during the off-season for each sport. All subjects provided written, informed consent within the guidelines of Edith Cowan University.

Isokinetic Dynamometry

A Biodex 3.0 (Shirley, NY) isokinetic dynamometer was used to measure peak torque values and torque-angle curves during knee flexion and extension. The subjects were seated on the Biodex with their hips flexed to approximately 90°. Their upper bodies were secured with dual crossover straps for the torso and a waist strap. The range of motion for the knee joint was set at approximately 110°, and the full leg extension position was set at 0° for knee extension and flexion. Lateral movements of the knee were restricted with a thigh strap, and an ankle strap was used to stabilize the lower leg. The subjects were instructed to grip side handles to help stabilize the upper body. Alignment between the center of rotation axis (i.e., the lateral femoral epicondyle) was monitored for each trial. Correction of gravity was obtained by measuring the torque exerted on the dynamometer lever arm by the weight of the arm.

All subjects performed 6 maximum concentric contractions (knee flexion and extension) for both legs in random order at an angular velocity of $60°\cdot s^{-1}$ (10). The raw data were transferred from the isokinetic dynamometer to a personal computer, on which the data were analyzed with a custom-made LabVIEW 8.2 (National Instruments) program. Torque and angle values were sorted according to the direction of the movement (i.e., knee flexion and extension). Of the 6 maximum effort knee flexions and extensions, the first and last contractions were excluded from the data analysis. In piloting, we found that torque levels occasionally decreased on the last repetition, and, thus, we wanted to exclude both the first and last repetitions. The second, third, fourth, and fifth contractions were averaged for determination of the optimum angle by fitting a fourth-order polynomial curve (torque and angle arrays) (22,23). Peak torque was determined from the peak of the fitted curve. The Q/H ratio was taken from the ratio of peak torque between the knee

TABLE 1. Comparison between cyclists and Australian rules football players (ARF) for the optimum angle and peak torque for the knee extensors and flexors, and quadriceps/hamstrings (Q/H) torque ratio.

	Cyclists	ARF
Knee extensors		
Optimum angle (°)	66.6 ± 5.9 (59.9–71.3)	70.8 ± 3.5* (66.2–73.7)
Peak torque (N·m)	181.4 ± 21.6 (138.3–223.7)	214.0 ± 33.4 (183.7–257.4)
Knee flexors		
Optimum angle (°)	32.3 ± 3.8 (27.3–39.1)	26.2 ± 2.9† (24.7–31.3)
Peak torque (N·m)	129.3 ± 20.9 (100.4–151.1)	143.4 ± 19.7 (115–167)
Q/H torque ratio	1.4 ± 0.14 (1.3–1.6)	1.5 ± 0.14 (1.4–1.7)

Values are mean ± SD for 9 subjects; values in parentheses are ranges. *Significantly different from the cyclist group ($p < 0.05$); †significantly different from cyclist group ($p < 0.01$).

between the subcutaneous adipose tissue and intermuscular interface was used to determine muscle thickness. Fascicle length was determined with the following formula (2,4): fascicle length = muscle thickness/sin (pennation angle). The coefficient of variation for muscle thickness, pennation angle, and fascicle length from the 3 images were 6.4, 5.8, and 6.1%, respectively.

Statistical Analyses

Mean and SD were used as measures of centrality and spread of data. Independent sample t-tests were used to determine differences in the criterion measures between groups. The statistical significance was set at $p ≤ 0.05$. The percent (%) differences were calculated as (high value − low value)/low value × 100.

extensors and flexors. The coefficients of variation for peak torque, optimum angle, and Q/H ratio from the 4 contractions were 6.7, 8.6, and 6.8%, respectively.

RESULTS

The mean values and SDs for all variables are shown in Tables 1 and 2. As shown in Table 1, the peak torque angle for the knee extensors was significantly ($p < 0.05$) larger for the ARF players compared with the cyclists. For knee flexion, the peak torque angle of the ARF players was significantly ($p < 0.01$) smaller than that of the cyclists. However, peak torque was not significantly different between groups for both knee flexion and extension. The Q/H ratio was not significantly different between the groups.

The ARF players had significantly ($p < 0.05$) smaller pennation angles and longer fascicle lengths as compared with the cyclists (Table 2). No significant differences in muscle thickness were observed between the groups.

Fascicle Length

Skeletal muscle architecture was assessed with B-mode ultrasound (model SSD-1000, Aloka, Tokyo, Japan) with a 7.5-MHz linear probe. The measurements were taken while the subjects stood balanced and relaxed, with their arms and legs extended. A water-soluble gel was applied to the probe to provide acoustic contact without depressing the dermal surface. The ultrasound probe was placed at the midway between the lateral condyle of the femur and greater trochanter, perpendicular to the VL, to record a cross-sectional image, and then the probe was shifted parallel to the VL for a longitudinal image. Muscle thickness, pennation angle, and fascicle length of the VL were measured from the ultrasound images using ImageJ software (U.S. National Institutes of Health, Bethesda, Md). Three ultrasound images were taken from the VL of the left legs, and the average of the 3 values for each variable was used for further analysis. The pennation angle was determined from the angle between the fascicle and deep aponeurosis (2,4). The distance

DISCUSSION

The present study found that cyclists produced peak torque at 66° during knee extension (i.e., shorter muscle lengths) in comparison with 70.3° in the ARF players. In similar cross-sectional papers, Herzog et al. (15) and Savelberg and Meijer (25) have reported that cyclists produced peak torque at shorter RF muscle fiber lengths in comparison with endurance runners. Savelberg and Meijer (25) also found that the optimum angles of the monoarticulate muscles (i.e., muscles that cross only 1 joint) produced peak torque at longer

TABLE 2. Comparison between cyclists and Australian rules football players (ARF) for muscle thickness, pennation angle, and fascicle length of the vastus lateralis.

	Cyclists	ARF
Muscle thickness (cm)	2.6 ± 0.3 (2.4–2.9)	2.6 ± 0.4 (2.4–3.0)
Pennation angle (°)	24.9 ± 2.5 (22.7–28.0)	19.3 ± 2.0* (17.6–20.5)
Fascicle length (cm)	6.2 ± 0.8 (5.5–6.8)	7.9 ± 0.7* (7.0–8.6)

Values are mean ± SD for 9 subjects; values in parentheses are ranges. *Significantly different from the cyclist group ($p < 0.05$).

lengths in the cyclists. Ullrich and Brueggemann (27) have reported that cyclists did not produce peak torque (quadriceps femoris) at significantly different joint angles in comparison with tennis players, endurance runners, and triathletes. The differences found between the study of Ullrich and Brueggemann (27) and previous studies may be explained by different testing methodologies and athletic groups. For example, the subjects in the study by Ullrich and Brueggemann (27) performed isometric contractions at different knee joint angles, and the optimum angle was determined from a second-order polynomial fitted curve. The present study measured isokinetic concentric contractions through a range of motion of 100° and used a fourth-order polynomial fitted curve. Second, the ARF players were unique to any of the groups previously tested. In ARF, players perform a mixture of training methods that require the athletes to contract their quadriceps femoris muscles eccentrically at long muscles fiber lengths, which include kicking in place, kicking while running, maximum velocity sprinting, accelerating, change of direction, bending over during running, jumping, and landing (5,26,28). In addition, ARF players perform intense endurance training as they routinely cover more than 15 km in a single game (14).

There are no studies, to our knowledge, that have investigated sport-related differences in optimum angle of peak torque during knee flexion. We feel that this is an important variable because the optimum angle has been related to hamstring injury rates in athletic populations. In the present study, the cyclists produced peak tension at shorter muscle fiber lengths (32.3°) than the ARF players (26.2°). Other studies have shown that ARF players with previous hamstring injuries produced peak torque at shorter muscle fiber lengths (40.9°) in comparison with noninjured athletes (29.8°) (12). In untrained subjects (8 men and 2 women), Brockett et al. (11) have reported optimum angles of peak torque of 38° during leg flexion. More research needs to be conducted in this area before the significance of these findings can be determined.

Muscle architecture (i.e., muscle thickness, pennation angle, and muscle fiber type) is thought to influence the functional properties of skeletal muscle with regard to shortening velocity, tension development, and resistance to fatigue (2–4,18). It is also thought that long-term sports training (>3 years) can influence muscle architecture and, ultimately, sport-related performance (2,4). There are no studies, to our knowledge, that have investigated the sport-related muscle architecture in trained cyclists. In the present study, the fascicle lengths of the cyclists were shorter and the pennation angles were greater than in the ARF players. However, muscle thickness values were not significantly different between the groups. The values for fascicle length and pennation angle were similar to those of endurance runners (6.15 cm) and untrained subjects (6.97–7.13 cm) as cited in previous research (3,19).

As shown in Table 2, the ARF players had significantly longer fascicle lengths (24.6%) and significantly smaller pennation angles (29.4%) in comparison with the cyclists. The values for the ARF players for fascicle lengths and pennation angles were similar to those of soccer players (7.7 cm and 21.6°) and sprinters (8.6 cm and 19°) in previous studies (3,18). However, sumo wrestlers and American football players had longer fascicle lengths (8.9–10.0 cm) and greater pennation angles (22.7–23.2°) in comparison with the ARF players in the present study (1,19). Increases in fascicle length and decreases in pennation angle are thought to have favorable implications for sprint performance (2,20) because both adaptations are thought to increase contraction shortening velocity. For example, Kumagai et al. (20) have reported significantly longer fascicle lengths of 8.4 vs. 5.98 cm and significantly smaller pennation angles of 17.7 vs. 20.1° for the elite female sprinters, in comparison with nonelite female sprinters. Abe et al. (3) have reported a similar significant difference between male elite and nonelite sprinters for fascicle length (8.6 vs. 7.5 cm) and pennation angle (19.0 vs. 21.1°). It seems that the fascicle lengths and pennation angles of the ARF players in the present study are better suited to running/sprinting performance and differ significantly from endurance cyclist profiles.

The Q/H ratios were not significantly different between groups in the present study. Previous research has reported similar Q/H ratios for ARF players, but little is known about the Q/H ratios of cyclists. None of the other architectural differences in the present study (i.e., pennation angle and fascicle length) seem to have influenced Q/H ratios or peak torque. It would be expected that the cyclists should express more force in comparison with the ARF players because they have greater pennation angles and similar muscle thickness levels. It seems that the significant architectural differences found in this study are not great enough to represent practical measurable force differences.

We feel that it is important to mention a few limitations of the present study. First, it is easy to assume that the differences found between athletic groups are caused by specific long-term sports training. It is just as easy to argue that other factors, such as genetics, could explain the differences between groups. In other words, an athletes who is genetically predisposed to be a cyclist may gravitate toward cycling. Second, ARF is a sport that uses a mixture of training methods, which include explosive jumping, acceleration, agility, maximum effort sprinting, kicking in place and on the run, periodized resistance training, and endurance training (5,26,28). Thus, it is difficult to identify which training stimulus had the main effect on the variables tested. Most likely, the results for the ARF players reflect a combined training effect of several types of loading stimuli. Finally, during knee extension, the present study did not differentiate between the biarticulate RF and the monoarticulate vasti muscles, which have different roles during explosive leg extensions. The monoarticulate muscles act mainly as work

and force generators, and the biarticulate muscles (i.e., crossing 2 joints) control the distribution of force and power between joints (9,16,17).

PRACTICAL APPLICATIONS

It is concluded that the ARF players have longer fascicle lengths, smaller pennation angles, and similar levels of knee extension strength, muscle thickness, and Q/H ratios compared with cyclists. These favorable architectural adaptations may be attributable to long-term (>3 years) sport-specific training. However, future research needs to investigate this contention. In terms of isokinetic assessment, it may be of great value for the strength practitioner to assess the torque-angle relationship of muscles such as the hamstring. This would provide valuable information for sports coaches, athletes, and practitioners. For example, athletes with shorter-than-normal optimum muscle lengths of tension development are thought to be at a higher risk of muscle strain injury during maximum effort running, jumping, acceleration, deceleration, and kicking (12,24). The effects of such assessment on identifying potential injury incidence in players/athletes– and, thereafter, the effect of training programs such as eccentrics–on changes in the angle of peak torque and in the incidence of injury and functional sports performance need to be investigated. Finally, because it is thought that muscle architecture is probably a greater determinant of general muscle function compared with other aspects such as fiber type (Blazevich et al. [8]), it would be of great value to map changes in fascicle length and pennation angle and associated changes in functional performance.

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