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original research

Quadriceps Function After Exercise in Patients with Anterior Cruciate Ligament–Reconstructed Knees Wearing Knee Braces

Alexis G. Davis, MEd, ATC*; Brian G. Pietrosimone, PhD, ATC†; Christopher D. Ingersoll, PhD, ATC, FNATA, FACSM‡; Kelli Pugh, MS, ATC, CMT§; Joseph M. Hart, PhD, ATC§

*Crest High School, Shelby, NC; †University of Toledo, OH; ‡Central Michigan University, Mt. Pleasant; §University of Virginia, Charlottesville

Context: Knee braces and neoprene sleeves are commonly worn by people with anterior cruciate ligament reconstructions (ACLRs) during athletic activity. How knee braces and sleeves affect muscle activation in people with ACLRs is unclear.

Purpose: To determine the effects of knee braces and neoprene knee sleeves on the quadriceps central activation ratio (CAR) before and after aerobic exercise in people with ACLRs.

Design: Crossover study.

Patients or Other Participants: Fourteen people with a history of ACLR (9 women, 5 men: age = 23.61 ± 4.44 years, height = 174.09 ± 9.82 cm, mass = 75.35 ± 17.48 kg, months since ACLR = 40.62 ± 20.41).

Intervention(s): During each of 3 sessions, participants performed a standardized aerobic exercise protocol on a treadmill. The independent variables were condition (brace, sleeve, or control) and time (baseline, pre-exercise with brace, postexercise with brace, postexercise without brace).

Main Outcome Measure(s): Normalized torque measured during a maximal voluntary isometric contraction (T_{MVIC}) and CAR were measured by a blinded assessor using the superimposed burst technique. The CAR was expressed as a percentage of full muscle activation. The quadriceps CAR and T_{MVIC} were measured 4 times during each session: baseline, pre-exercise with brace, postexercise with brace, and postexercise without brace.

Results: Immediately after the application of the knee brace, T_{MVIC} decreased ($P = .01$), but no differences between bracing conditions were observed. We noted reduced T_{MVIC} and CAR ($P < .001$) after exercise, both with and without the brace. No differences were seen between bracing conditions after aerobic exercise.

Conclusions: The decrease in T_{MVIC} immediately after brace application was not accompanied by differences between bracing conditions. Wearing a knee brace or neoprene sleeve did not seem to affect the deterioration of quadriceps function after aerobic exercise.

Key Words: neuromuscular function, aerobic exercise, central activation ratio

Key Points

- After a single bout of aerobic exercise, people with anterior cruciate ligament reconstructions displayed reduced quadriceps normalized maximal voluntary isometric torque and central activation ratio. These reductions were not affected by wearing a knee brace or neoprene sleeve while exercising.
- Once the knee brace was applied, quadriceps normalized maximal voluntary isometric torque decreased immediately, but the central activation ratio did not change.
- Wearing a knee brace or neoprene sleeve neither helped nor hindered quadriceps function during a single bout of aerobic exercise.

Quadriceps muscle weakness and central activation failure[1] are common after anterior cruciate ligament (ACL) injury and reconstruction (ACLR).[2,3] The phenomenon of persistent weakness and activation failure may be explained by arthrogenic muscle inhibition, a reflex response to joint injury that may be magnified after aerobic exercise[4] in which a muscle cannot contract to its full potential.[2,3] Persistent quadriceps weakness after knee joint injury is a likely cause of altered gait patterns[5] and shock attenuation capabilities during dynamic activities.[6] Identifying potential sources of arthrogenic muscle inhibition and therapies to help overcome inhibition is paramount to preventing excessive muscle weakness and altered lower extremity biomechanics after joint injury.

Conventionally, a variety of knee braces have been prescribed to assist people with ACLRs maintain joint stability and prevent further joint injury during exercise.[7,8] Rigid braces and neoprene sleeves are often worn during athletic activity[9–11] for a variety of reasons; however, little is known about how braces and sleeves influence neuromuscular adaptations during exercise. Quadriceps muscle function has been shown to deteriorate after a standardized treadmill aerobic exercise protocol.[12] This finding is clinically important because knee braces or sleeves are often worn after ACLR during athletic activities, yet whether such braces help or hinder neuromuscular function of the quadriceps, which is known to be deficient after ACL injury and ACLR, is unknown.[13] Although decreases in muscle activation may occur during aerobic exercise, clinicians should be aware of the influence of external knee joint bracing on quadriceps function in people with ACLRs during prolonged exercise. The purposes of our study were to compare (1) the quadriceps muscle central activation ratio (CAR) and normalized torque measured during a maximal voluntary isometric contraction (T_{MVIC}) immediately after the application of a rigid knee brace or neoprene sleeve and (2) changes in CAR and T_{MVIC} after aerobic exercise in people with ACLRs wearing a knee brace or neoprene sleeve while exercising.

METHODS

Participants

A total of 18 people with ACLRs were enrolled in the study, but 4 withdrew before completing all sessions. Therefore, 14 volunteers (9 women, 5 men: age = 23.61 ± 4.44 years, height = 174.09 ± 9.82 cm, mass = 75.35 ± 17.48 kg) with primary, unilateral ACLR who had undergone surgery (8 hamstring autografts, 5 bone–patellar tendon–bone autografts) at least 2 years earlier (mean = 40.62 ± 20.41 months) completed all sessions. Volunteers were excluded from the study if they had undergone graft revision or multiple knee ligament repairs, experienced infection or another postoperative complication that necessitated surgical intervention, or had continued complaints of pain or instability. This study was approved by the institutional review board before participant recruitment, and each participant provided written informed consent before enrolling.

Instruments

Isometric torque was recorded by a dynamometer (Biodex System 3; Biodex Medical Systems, Inc, Shirley, NY) and exported through a remote access port via a custom-built coaxial cable to a 16-bit analog-to-digital converter (model MP150; BIOPAC Systems, Inc, Goleta, CA), where it was digitized (200 Hz). A square-wave stimulator (model S88; Grass Technologies, West Warwick, RI) in conjunction with a stimulation isolation unit (model SIU8T; Grass Technologies) produced a 100-millisecond train of 10 stimuli at 100 pulses per second, with a pulse duration of 0.6 milliseconds and a 0.01-millisecond pulse delay. With the low switch engaged on the stimulation isolation unit and an estimated 3000-Ω load, each participant was stimulated with approximately 125 V. Two 7-×13-cm Dura Stick II self-adhesive electrodes (Chattanooga Group, Hixson, TN) were used to deliver the stimulus to the quadriceps muscles.

Testing Procedures

All participants completed 1 aerobic exercise familiarization session and 3 measurement testing sessions. During the 3 testing sessions, each participant performed a bout of standardized aerobic exercise while wearing a knee brace, neoprene sleeve, or nothing (control). During each session, quadriceps muscle testing was repeated 4 times: (1) baseline before exercise and bracing condition, (2) before exercise with randomly allocated bracing condition applied, (3) after exercise with randomly allocated bracing condition remaining, and (4) after exercise with bracing condition removed.

Apart from the initial exercise familiarization session, the order of the testing sessions was counterbalanced by an investigator who was not collecting the measurements and the sessions were separated by at least 7 days. The investigator collecting all outcome measurements left the room while another investigator randomly allocated bracing condition, appropriately fit the participant with the specific brace or sleeve (each fitting took approximately 5 minutes), and supervised the aerobic exercise. During quadriceps muscle testing, a screen was used to blind this investigator.

Bracing Conditions

The knee brace was an off-the-shelf ACL functional brace designed to prevent anterior tibial translation using rigid anterior cuffs and soft posterior straps (Fusion; Breg Inc, Vista, CA). The neoprene knee sleeve was a typical soft support sleeve with a closed patella designed to provide compression and warmth to the knee joint (Knee Support; Breg Inc). During the control sessions, participants were treated exactly the same as when they were fitted with the knee brace or neoprene sleeve. They were removed from the chair for the same approximate time that it would take to fit the knee brace or neoprene sleeve and then restrapped into the chair with no brace on the knee.

After the aerobic exercise, participants were immediately restrapped into the chair for the postaerobic exercise test with the assigned brace or sleeve condition. They were removed from the chair, so the brace or sleeve could be taken off, and then restrapped into the chair for the second postaerobic exercise test. In the control sessions, participants were removed from the chair between postaerobic exercise tests for the same amount of time. The time between postaerobic exercise tests was kept under approximately 2 minutes to reduce potential confounding due to recovery.

Aerobic Exercise

Each participant completed a 20-minute treadmill exercise protocol at a constant walking speed of 3.5 mph (5.6 km/h). Each minute for the first 15 minutes, the treadmill level of incline was increased by 1%. While on the treadmill, participants provided a subjective rating of perceived exertion (RPE)[14] every minute to ensure they did not exceed an RPE of 17. The scale provides numerical values ranging from 6 (*no exertion*) to 20 (*maximal exertion*); 17 corresponds to the perception that the exercise is *very hard*. However, during the last 5 minutes of exercise, participants adjusted the treadmill grade (up or down) so that they were exercising within the desired range of exercise intensity (RPE rating of at least 15 but no more than 17). Before the 3 testing sessions, each participant performed a treadmill familiarization session, in which he or she executed the exercise protocol in order to establish the treadmill settings and adjustments that could be repeated exactly during all 3 experimental sessions.

Quadriceps Central Activation Ratio Testing

Two 8-×14-cm self-adhesive electrodes were applied to a clean, dry surface on the participant's proximal-lateral and distal-medial thigh. The top of the proximal electrode was positioned at the height of the greater trochanter, with the medial edge of the electrode aligned with the anterior-superior iliac spine, while the bottom of the distal electrode was positioned 2 cm proximal to the superior pole of the patella, with the medial edge aligned with the middle of the patella.

The participant was positioned in the dynamometer chair with the back at an 85° angle and the knee in 90° of flexion. The distal lower leg was tightly secured to the arm of the dynamometer with a hook-and-loop strap and was positioned proximal to the ankle mortise. Hook-and-loop straps secured the participant to the seat at both shoulders and the waist.

Each participant performed several submaximal and maximal practice contractions to allow for adequate warmup before baseline testing. During test trials, verbal feedback and instruction were provided for the maximal isometric knee extension contraction to encourage proper technique. Once the examiner observed a plateau in torque, electric stimulation was manually triggered and delivered through the thigh electrodes. This stimulus resulted in a transient increase in isometric torque, called the superimposed burst torque (T_{SIB}) production, which represents the torque produced by activating unrecruited portions of the quadriceps muscle via exogenous stimulus. The average of 2 trials, separated by a 30-second rest period, was used for analysis.

Data Analysis

The quadriceps CAR was calculated for each participant to express the percentage of muscle that could be voluntarily activated. The CAR was calculated by dividing the normalized T_{MVIC} by the normalized T_{SIB} using the following formula: $T_{MVIC}/T_{SIB} \times 100$. The T_{MVIC} was calculated from a 0.1-second time epoch immediately before the electric stimulus was administered. All torques were normalized to body mass.

Statistical Analysis

The sample size was an estimate based on variability in CAR of approximately 8% to 10% in people with ACLRs.[13] We anticipated a large effect size (ie, >0.8) in the change in CAR after the treadmill exercise protocol, so 14 participants were deemed sufficient for our analysis with an acceptable 5% type I error rate and statistical power of 80%. We oversampled to compensate for the likelihood of dropout in a 4-session crossover design.

Within-session reliability of torque and CAR measurements was evaluated using the control session pre-exercise data, and between-sessions reliability by evaluating the baseline measures from each session. We used intraclass correlation coefficients (ICCs) for reliability analysis.

This was a repeated-measures, pretest-posttest crossover design. The independent variables were bracing condition (knee brace, neoprene sleeve, control) and time (baseline, pre-exercise with brace condition applied, postexercise with brace condition, postexercise with brace condition removed). The dependent variables were CAR (%) and T_{MVIC} (Nm/kg). To compare T_{MVIC} and CAR immediately after the application of each knee bracing condition, we performed a 2×3 analysis of variance with repeated measures on the 2 pre-exercise measurements (baseline and pre-exercise with brace condition). We then performed 2 separate 2×3 analyses of variance with repeated measures for each dependent variable to determine the pretest-posttest exercise changes in quadriceps muscle function. These tests were performed to compare pre-exercise and postexercise measures recorded with and without the bracing condition.

Post hoc comparisons between the bracing conditions (Tukey least significant difference) were performed where appropriate. We also calculated within-bracing condition effect sizes (Cohen d = mean difference/pooled standard deviation) for all main effects. All statistical tests were performed using SPSS (version 17.0; SPSS Inc, Chicago, IL). A test was considered statistically significant if the P value was .05 or less.

RESULTS

Reliability of Measurements

The ICC from the control session (no brace) indicated high within-day reliability for CAR (ICC [1,k] = 0.978) and T_{MVIC} (ICC [1,k] = 0.972; Table). Between-days reliability was also high for CAR (ICC [2,k] = 0.95) and T_{MVIC} (ICC [2,k] = 0.92).

Immediate Effects of Brace Application

This analysis compared baseline and pre-exercise measurements with the brace condition applied. A reduction was noted in T_{MVIC} ($F_{1,39} = 6.9$, $P = .01$) but not in CAR ($F_{1,39} = 0.59$, $P = .45$) immediately after the knee bracing condition was applied. No bracing condition differences or bracing condition-by-time interaction were observed (Table). Effect sizes describing the changes in T_{MVIC} measures in each bracing condition were control = 0.07, knee brace = 0.20, and neoprene sleeve = 0.21; for CAR, they were control = 0.04, knee brace = –0.16, and neoprene sleeve = –0.07.

Table. Central Activation Ratio (CAR, %) and Normalized Maximal Voluntary Isometric Torque (T_{MVIC}, Nm/kg) by Bracing Condition and Time, Mean ± SD

		Time			
Bracing Condition		Baseline	Pre-Exercise (Brace Condition Applied)	Postexercise (Brace Condition Applied)	Postexercise (Brace Condition Removed)
Control	CAR	90.04 ± 9.89	89.61 ± 11.64	85.62 ± 11.85	87.11 ± 11.93
	T_{MVIC}	2.82 ± 0.88	2.76 ± 0.87	2.53 ± 0.85	2.57 ± 0.80
Knee brace	CAR	89.99 ± 9.55	91.37 ± 7.97	87.26 ± 10.71	87.52 ± 9.74
	T_{MVIC}	2.80 ± 0.78	2.66 ± 0.60	2.55 ± 0.62	2.60 ± 0.63
Neoprene sleeve	CAR	92.65 ± 7.89	92.40 ± 5.79	87.90 ± 9.07	88.63 ± 8.24
	T_{MVIC}	2.96 ± 0.72	2.76 ± 0.70	2.56 ± 0.63	2.58 ± 0.56
Total[c]	CAR	90.75 ± 9.08	91.03 ± 8.85	86.85 ± 10.48[a]	87.68 ± 9.95[b]
	T_{MVIC}	2.85 ± 0.78	2.72 ± 0.72[b]	2.55 ± 0.69[a]	2.58 ± 0.66[b]

Abbreviations: CAR indicates central activation ratio; T_{MVIC}, normalized torque measured during a maximal voluntary isometric contraction.
[a] Significantly lower than pre-exercise measures recorded with the bracing condition applied ($P < .05$).
[b] Significantly lower than baseline.

Effects of Wearing Braces During Aerobic Exercise

This analysis compared data measured at pre-exercise with bracing condition applied and after exercise with the bracing condition remaining. On average, participants experienced a reduction in CAR ($F_{1,39}=41.2$, $P<.001$) and T_{MVIC} ($F_{1,39}=27.7$, $P<.001$) during the allocated knee bracing condition. No differences were seen between bracing condition (main effects), and no interactions were demonstrated. We calculated effect sizes describing within-bracing condition changes in T_{MVIC} (control = 0.26, knee brace = 0.18, and neoprene sleeve = 0.34) and CAR (control = 0.34, knee brace = 0.44, and neoprene sleeve = 0.57).

In the analysis that compared data measured at baseline and after exercise with the bracing condition removed, we observed a reduction in CAR ($F_{1,39}=9.7$, $P=.003$) and T_{MVIC} ($F_{1,39}=23.7$, $P<.001$) when quadriceps function was measured with the allocated knee bracing condition removed. No differences were evident between bracing condition groups (main effects) and no interactions were noted. We calculated effect sizes for each group to describe changes in T_{MVIC} (control = 0.30, knee brace = 0.28, and neoprene sleeve = 0.51) and CAR (control = 0.26, knee brace = 0.25, and neoprene sleeve = 0.23).

DISCUSSION

Our findings are consistent with those of previous researchers[15–17] who demonstrated a decrease in quadriceps muscle function and activation after aerobic exercise. Although numerous authors have looked at the effects of knee braces[18–29] and neoprene sleeves[10,30] on neuromuscular performance during dynamic activities, very few have compared these effects during a bout of aerobic exercise. Previous studies of knee bracing and neuromuscular function have indicated that knee braces[21,22,24,26–28] decreased quadriceps muscle function and that neoprene sleeves[10,30] improved knee joint proprioception. Our findings indicate that knee braces and neoprene sleeves did not affect the reductions in quadriceps T_{MVIC} or CAR that were observed after aerobic exercise.

Although we saw no differences among sessions, T_{MVIC} and CAR were lower than baseline values after exercise during all sessions. This result is consistent with the results of earlier authors[31,32] who showed decreases in muscle function after aerobic exercise in healthy people; however, we believe we are the first to evaluate quadriceps muscle function in people with ACLRs wearing knee braces. Persistent quadriceps dysfunction[13] and altered gait patterns[33] after ACLR are well documented and may be exacerbated during prolonged exercise bouts, possibly because of excessive muscle fatigability or inappropriate neuromuscular adaptations. People with ACLRs commonly wear braces while active; therefore, it is important to understand whether muscles respond differently during exercise when a brace is worn. Whether the response represents an improvement or deterioration, clinicians should be informed in order to make evidence-based recommendations to athletes and patients. In our study, no changes were apparent in quadriceps muscle function immediately after knee braces were applied. Furthermore, the deterioration in quadriceps strength and central activation after a single session of aerobic exercise in people with ACLRs was not influenced by either of the bracing conditions.

The immediate application of a knee brace or a neoprene sleeve before exercise did not affect CAR; however, T_{MVIC} values immediately decreased, indicating that knee extensor strength was affected but central activation was not. One possible explanation is that cutaneous afferent feedback from brace or sleeve application resulted in a proportional reduction in both T_{MVIC} and T_{SIB}. Previous researchers[34–37] demonstrated that providing direct cutaneous stimulation, such as hot and cold, can change afferent responses to the central nervous system. Pietrosimone and Ingersoll[36] reported that both transcutaneous electric nerve stimulation and cryotherapy immediately increased quadriceps CAR in participants with knee joint osteoarthritis, suggesting that afferent feedback from an external source may alter quadriceps CAR. In the current study, we observed larger effect sizes in the braced conditions than in the control condition, which may reflect increased cutaneous mechanoreceptor stimulation from greater surface area contact with the skin surrounding the knee joint. However, only torque production was affected; quadriceps CAR was not.

Bracing in people with ACLRs is controversial when the potential risks and benefits during exercise are considered, especially for joint stability, neuromuscular function, and performance. For example, bracing has resulted in altered knee joint proprioception[19,30] and been found to hinder athletic performance.[21,24,26,27] The added bulk and weight of braces may also be concerning to athletes.[27,28] Therefore, whether a person with an ACLR should wear a brace must be determined in light of the potential advantages and disadvantages. However, according to our results, wearing a brace or knee sleeve during aerobic exercise did not influence the change in torque production or central drive to the quadriceps in people with ACLRs.

Research on the clinical effects of knee braces continues to show conflicting findings. Numerous authors[38–41] have indicated that a knee brace may decrease the amount of shear forces and anterior tibial translation at the knee joint, improving the perception of stability. Previous investigations[34,37] on the role of mechanoreceptors in joint position sense have demonstrated that feedback from skin receptors can affect joint proprioception. This may explain why knee bracing appears to improve proprioception in fatigued people and in those with preexisting proprioceptive deficits.[10] Yet people with ACLRs who wore a knee brace displayed improved neuromuscular control during drop landings.[42] We did not determine whether any of our participants had specific proprioceptive or neuromuscular deficits; therefore, any potential benefit would have been mitigated in a participant without pre-existing deficiencies. In our cohort of young, healthy, and recreationally active people with ACLRs, bracing did not seem to help or hinder quadriceps muscle function after aerobic exercise.

A limitation to the current study is the small sample size and the fact that participants may or may not have had experience with wearing knee braces during activity. Each brace was worn for only 1 session, so the effects of a knee brace or neoprene sleeve over a longer period of time, such as the length of a sport season, are unknown. The long-term effects of wearing knee braces for active people with ACLRs have not been studied. It is also possible that alterations in participants' gait patterns from wearing the braces[22] affected knee joint biomechanics; observations of people with ACLRs during more sport-specific exercises and more prolonged bouts of exercise may provide additional information about muscle function in the braced knee. We did not screen participants for quadriceps muscle activation failure, nor did we measure quadriceps function bilaterally. Some participants were more than 95% activated, which has been defined as "fully activated."[1] In the current study, 8 of 14 participants in each session exhibited quadriceps central activation failure (CAR values less than 95%) at the baseline measure. The effect of a knee brace or neoprene sleeve may be different if used on a population of knee-injured participants with documented quadriceps central activation failure or asymmetric quadriceps neuromuscular function.

In conclusion, T_{MVIC} and CAR decreased after a single bout of aerobic exercise in people with ACLRs, a finding that was not affected by wearing a knee brace or neoprene sleeve while exercising. Quadriceps CAR was not altered after a knee brace was applied, but T_{MVIC} was immediately reduced. Therefore, according to our findings, wearing a knee brace or neoprene sleeve neither helped nor hindered quadriceps muscle function during a single bout of aerobic exercise.

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REFERENCES

1. Stackhouse SK, Stevens JE, Lee SC, Pearce KM, Snyder-Mackler L, Binder-Macleod SA. Maximum voluntary activation in nonfatigued and fatigued muscle of young and elderly individuals. *Phys Ther.* 2001;81(5):1102–1109.
2. Chmielewski TL, Stackhouse S, Axe MJ, Snyder-Mackler L. A prospective analysis of incidence and severity of quadriceps inhibition in a consecutive sample of 100 patients with complete acute anterior cruciate ligament rupture. *J Orthop Res*. 2004;22(5):925–930.
3. Urbach D, Nebelung W, Becker R, Awiszus F. Effects of reconstruction of the anterior cruciate ligament on voluntary activation of quadriceps femoris: a prospective twitch interpolation study. *J Bone Joint Surg Br.* 2001;83(8):1104–1110.
4. Milner-Brown HS, Miller RG. Increased muscular fatigue in patients with neurogenic muscle weakness: quantification and pathophysiology. *Arch Phys Med Rehabil*. 1989;70(5):361–366.
5. Torry MR, Decker MJ, Ellis HB, Shelburne KB, Sterett WI, Steadman JR. Mechanisms of compensating for anterior cruciate ligament deficiency during gait. *Med Sci Sports Exerc*. 2004;36(8):1403–1412.
6. Palmieri-Smith RM, Kreinbrink J, Ashton-Miller JA, Wojtys EM. Quadriceps inhibition induced by an experimental knee joint effusion affects knee joint mechanics during a single-legged drop landing. *Am J Sports Med.* 2007;35(8):1269–1275.
7. McDevitt ER, Taylor DC, Miller MD, et al. Functional bracing after anterior cruciate ligament reconstruction: a prospective, randomized, multicenter study. *Am J Sports Med*. 2004;32(8):1887–1892.
8. Wright RW, Fetzer GB. Bracing after ACL reconstruction: a systematic review. *Clin Orthop Relat Res*. 2007;455:162–168.
9. Miller AA, Knight KL, Feland JB, Draper DO. Neoprene thigh sleeves and muscle cooling after exercise. *J Athl Train*. 2005;40(4):264–270.
10. Tiggelen DV, Coorevits P, Witvrouw E. The effects of a neoprene knee sleeve on subjects with a poor versus good joint position sense subjected to an isokinetic fatigue protocol. *Clin J Sport Med*. 2008;18(3):259–265.
11. Chew KT, Lew HL, Date E, Fredericson M. Current evidence and clinical applications of therapeutic knee braces. *Am J Phys Med Rehabil*. 2007;86(8):678–686.
12. Hart JM, Weltman A, Ingersoll CD. Quadriceps activation following aerobic exercise in persons with low back pain and healthy controls. *Clin Biomech (Bristol, Avon)*. 2010;25(8):847–851.
13. Hart JM, Pietrosimone B, Hertel J, Ingersoll CD. Quadriceps activation following knee injuries: a systematic review. *J Athl Train*. 2010;45(1):87–97.
14. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377–381.
15. Edwards RH, Hill DK, Jones DA, Merton PA. Fatigue of long duration in human skeletal muscle after exercise. *J Physiol*. 1977;272(3):769–778.
16. Milner-Brown HS, Mellenthin M, Miller RG. Quantifying human muscle strength, endurance and fatigue. *Arch Phys Med Rehabil*. 1986;67(8):530–535.
17. Milner-Brown HS, Miller RG. Muscle membrane excitation and impulse propagation velocity are reduced during muscle fatigue. *Muscle Nerve*. 1986;9(4):367–374.
18. Beynnon BD, Good L, Risberg MA. The effect of bracing on proprioception of knees with anterior cruciate ligament injury. *J Orthop Sports Phys Ther.* 2002;32(1):11–15.
19. Beynnon BD, Ryder SH, Konradsen L, Johnson RJ, Johnson K, Renstrom PA. The effect of anterior cruciate ligament trauma and bracing on knee proprioception. *Am J Sports Med*. 1999;27(2):150–155.
20. Birmingham TB, Bryant DM, Giffin JR, et al. A randomized controlled trial comparing the effectiveness of functional knee brace and neoprene sleeve use after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2008;36(4):648–655.
21. Birmingham TB, Kramer JF, Kirkley A. Effect of a functional knee brace on knee flexion and extension strength after anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil*. 2002;83(10):1472–1475.
22. DeVita P, Lassiter T Jr, Hortobagyi T, Torry M. Functional knee brace effects during walking in patients with anterior cruciate ligament reconstruction. *Am J Sports Med*. 1998;26(6):778–784.
23. Fleming BC, Renstrom PA, Beynnon BD, Engstrom B, Peura G. The influence of functional knee bracing on the anterior cruciate ligament strain biomechanics in weightbearing and nonweightbearing knees. *Am J Sports Med*. 2000;28(6):815–824.
24. Houston ME, Goemans PH. Leg muscle performance of athletes with and without knee support braces. *Arch Phys Med Rehabil*. 1982;63(9):431–432.
25. Kaminski TW, Perrin DH. Effect of prophylactic knee bracing on balance and joint position sense. *J Athl Train*. 1996;31(2):131–136.
26. Sforzo GA, Chen NM, Gold CA, Frye PA. The effect of prophylactic knee bracing on performance. *Med Sci Sports Exerc*. 1989;21(3):254–257.
27. Styf J. The effects of functional knee bracing on muscle function and performance. *Sports Med*. 1999;28(2):77–81.
28. Veldhuizen JW, Koene FM, Oostvogel HJ, von Thiel TP, Verstappen FT. The effects of a supportive knee brace on leg performance in healthy subjects. *Int J Sports Med*. 1991;12(6):577–580.
29. Wu GK, Ng GY, Mak AF. Effects of knee bracing on the functional performance of patients with anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil*. 2001;82(2):282–285.
30. Chuang SH, Huang MH, Chen TW, Weng MC, Liu CW, Chen CH. Effect of knee sleeve on static and dynamic balance in patients with knee osteoarthritis. *Kaohsiung J Med Sci*. 2007;23(8):405–411.
31. Lepers R, Hausswirth C, Maffiuletti N, Brisswalter J, van Hoecke J. Evidence of neuromuscular fatigue after prolonged cycling exercise. *Med Sci Sports Exerc*. 2000;32(11):1880–1886.
32. Lepers R, Maffiuletti NA, Rochette L, Brugniaux J, Millet GY. Neuromuscular fatigue during a long-duration cycling exercise. *J Appl Physiol*. 2002;92(4):1487–1493.
33. Hart JM, Ko JW, Konold T, Pietrosimione B. Sagittal plane knee joint moments following anterior cruciate ligament injury and reconstruction: a systematic review. *Clin Biomech (Bristol, Avon)*. 2010;25(4):277–283.
34. Grigg P. Properties of sensory neurons innervating synovial joints. *Cells Tissues Organs*. 2001;169(3):218–225.
35. Pietrosimone BG, Hart JM, Saliba SA, Hertel J, Ingersoll CD. Immediate effects of transcutaneous electrical nerve stimulation and focal knee joint cooling on quadriceps activation. *Med Sci Sports Exerc*. 2009;41(6):1175–1181.
36. Pietrosimone BG, Ingersoll CD. Focal knee joint cooling increases the quadriceps central activation ratio. *J Sports Sci*. 2009;27(8):873–879.
37. Grigg P. Peripheral neural mechanisms in proprioception. *J Sport Rehabil*. 1994;3(1):2–17.
38. Wojtys EM, Loubert PV, Samson SY, Viviano DM. Use of a knee-brace

for control of tibial translation and rotation: a comparison, in cadavera, of available models. *J Bone Joint Surg Am*. 1990;72(9):1323–1329.
39. Cawley PW, France EP, Paulos LE. Comparison of rehabilitative knee braces: a biomechanical investigation. *Am J Sports Med*. 1989;17(2): 141–146.
40. Millet CW, Drez DJ Jr. Principles of bracing for the anterior cruciate ligament–deficient knee. *Clin Sports Med*. 1988;7(4):827–833.
41. Branch T, Hunter R, Reynolds P. Controlling anterior tibial displacement under static load: a comparison of two braces. *Orthopedics*. 1988;11(9):1249–1252.
42. Rebel M, Paessler HH. The effect of knee brace on coordination and neuronal leg muscle control: an early postoperative functional study in anterior cruciate ligament reconstructed patients. *Knee Surg Sports Traumatol Arthrosc*. 2001;9(5):272–281.

Address correspondence to Joseph M. Hart, PhD, ATC, University of Virginia, Department of Human Services, PO Box 400407, Charlottesville, VA 22904. Address e-mail to jmh3zf@virginia.edu.