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Functional bracing of ACL injuries: current state and future directions

Sean D. Smith · Robert F. LaPrade ·
Kyle S. Jansson · Asbjørn Årøen · Coen A. Wijdicks

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Abstract
Purpose Functional braces are commonly prescribed to treat anterior cruciate ligament (ACL) injury. The results of the existing literature on functional brace use are mixed. The purpose of this study was to evaluate the history and current state of functional ACL bracing and to identify design criteria that could improve upon current bracing technologies.
Methods A literature search was performed through the PubMed MEDLINE database in April 2013 for the keywords "anterior cruciate ligament" and "brace". Articles published between January 1, 1980, and April 4, 2013, were retrieved and reviewed. Current functional braces used to treat ACL injury were identified. The function of the native ACL was carefully studied to identify design requirements that could improve upon current bracing technologies.
Results Biomechanical evaluations of functional brace effects at time zero have been mixed. Functional brace use reportedly does not improve long-term patient outcomes following ACL reconstruction, but has been shown to reduce subsequent injury rates while skiing in both ACL-deficient and reconstructed skiers. In situ force in the ACL varies with flexion angle and activity. Currently, no brace has been designed and validated to replicate the force-flexion behavior of the native ACL.
Conclusions Biomechanical and clinical evidence suggests current functional bracing technologies do not sufficiently restore normal biomechanics to the ACL-deficient knee, protect the reconstructed ACL, and improve long-term patient outcomes. Further research into a functional brace designed to apply forces to the knee joint similar in magnitude to the native ACL should be pursued.
Level of evidence III.

Keywords Anterior cruciate ligament · Functional brace · Deficiency · Reconstruction

Introduction

In the USA, there are approximately 200,000 anterior cruciate ligament (ACL) injuries per year [26]. Over half of these injuries undergo ACL reconstruction, which results in close to 100,000 ACL reconstructions annually or 32 per 100,000 citizens [26, 51, 59]. Similar annual incidence of ACL reconstructions has been reported in Denmark, Norway, Sweden, and Germany, with even higher incidence rates of 70–91 per 100,000 for at-risk age groups less than 40 years of age [30, 31, 47, 49]. ACL tears result in altered tibiofemoral kinematics and joint contact mechanics [5]. Meniscal tears and osteoarthritis are commonly associated with ACL injuries [16, 42]. Additionally, residual instability, neuromuscular deficits, and altered lower extremity biomechanics following ACL injury and reconstruction can result in overcompensation and altered biomechanics in the contralateral leg and an increased risk of secondary injury

S. D. Smith · R. F. LaPrade · K. S. Jansson · A. Årøen ·
C. A. Wijdicks (✉)
Department of BioMedical Engineering, Steadman Philippon Research Institute (SPRI), 181W. Meadow Drive, Suite 1000, Vail, CO 81657, USA
e-mail: cwijdicks@sprivail.org
URL: www.sprivail.org

R. F. LaPrade
The Steadman Clinic, Vail, CO, USA

A. Årøen
Department of Orthopaedic Surgery, Akershus University Hospital, University of Oslo, Oslo, Norway

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in both the injured and contralateral knees [27, 34, 60, 79]. Anatomic reconstructions have attempted to restore stability to the intact state with improved tunnel placement [62, 90]; however, elongation of the ACL graft during the healing process remains unrestrained [14]. Additionally, graft failure rates following anatomic reconstruction have been reported to be as high as 13 % [80]. In situ forces in anatomically placed ACL grafts have been reported in vitro to be similar to the native ACL and higher than in non-anatomical reconstructions, which may explain the increased rates of graft failure following anatomic reconstruction [61, 66, 80]. Graft material also reportedly influences the occurrence of graft failures, with higher revision rates reported for allografts versus autografts and hamstring grafts versus bone-patellar tendon bone (BPTB) grafts [4, 48]; a slower ligamentization process reportedly is observed with allografts [36, 57, 83]. The treatment for ACL injuries often involves the use of a functional brace to help achieve an optimal result and avoid the described complications. Functional brace use has been reported for:

- Postoperative stabilization to theoretically allow normal tibiofemoral kinematics while preventing excessive strain and elongation of the healing ACL graft [13, 15, 54, 63, 82].
- Non-operative treatment for chronic ACL deficiency to prevent subsequent injury and reduce functional deficits [25, 41].
- ACL injuries in skeletally immature individuals to prevent subsequent injury until maturity is reached and reconstruction can be performed without damaging the epiphyseal growth plates [56].
- Pre-operative stabilization of the knee joint to prevent subsequent meniscal and chondral injuries until surgery can be performed [50].

According to a survey of the American Orthopaedic Society for Sports Medicine (AOSSM), only 13 % of surgeons never prescribe functional brace use to their ACL reconstruction patients and only 3 % never brace their ACL-deficient patients [23]. A separate survey of the AOSSM reported 63 % of surgeons prescribe functional brace use for their ACL reconstruction patients, 71 % of which prescribe brace use for up to 1 year [25]. As a result, numerous functional braces have been developed to treat ACL deficiency and to improve patient outcomes following ACL reconstructions (Table 1; Fig. 1). This underlines the fact that there is large demand for functional braces. Based on the reported numbers of annual ACL injuries in the USA and Scandinavia and brace prescription rates reported by members of the AOSSM, it is reasonable to assume that more than 100,000 functional braces are prescribed each year in the USA and an additional 10,000 in Scandinavian countries to treat ACL injuries [23, 25, 26, 30, 31, 47, 59]. With an average cost of $592 USD, functional bracing of ACL injuries is placing a significant financial burden on the healthcare system; estimated at over $65,000,000 USD per year in the USA and Scandinavia.

While functional bracing of patients with ACL injury is common, most biomechanical and clinical studies do not support the use of current bracing technologies due to reported lack of control of anterior tibial translation (ATT), strain shielding of the ACL graft, and improvements in long-term patient outcomes [15, 19, 54, 63]. Given the high cost of braces and the limited evidence supporting use, a major scientific question is to understand the role of functional braces in the treatment for ACL injuries; specifically, what impact are braces having clinically on patient outcomes, what are the biomechanical limitations of current braces, and how can functional braces be improved? Therefore, the purpose of this systematic review was to critically evaluate the history and current state of ACL functional bracing based on clinical and biomechanical evidence and to identify design criteria founded on the function of the native ACL that could advance current technologies and improve patient outcomes.

Materials and methods

This article focused on the following topics: history of functional bracing for ACL injury, biomechanical characteristics of the native ACL, biomechanical evaluation of functional bracing for ACL injury, and clinical evaluation of functional bracing for ACL injury. A literature search was performed through the PubMed MEDLINE database (PubMed) in April 2013 for combinations of the keywords "anterior cruciate ligament" and "brace". Articles published between January 1, 1980, and April 4, 2013, were retrieved, and the titles, abstracts, and text were reviewed for relevance to the topics of this study. The keyword literature search for "anterior cruciate ligament brace" returned 261 results. Relevant articles were retained and more critically reviewed for information pertinent to this article. Reference sections of the initially gathered literature were reviewed for additional relevant studies. The clinical evidence reviewed in this study consisted of three level 1 randomized controlled trials and two level 3 prospective cohort studies. Non-English language articles and studies focusing on rehabilitation and range of motion braces were excluded. Biomechanical and clinical studies reporting on existing ACL functional braces were thoroughly reviewed to identify areas where current bracing technologies could be improved. The reported biomechanical properties and function of the native ACL were used to determine evidence-based design requirements for future functional brace development.

Table 1 Comparison of commercially available functional braces commonly prescribed to treat ACL injury as of April 2013

Manufacturer	Model	Cost ($)[a]	Material	Design highlights	Recommended usage	Custom/OTS
Albrecht	Jack ACL	1,300.00	Aluminum	Constant posterior-directed translation force, 15 adjustable levels of spring tension	Activities of daily living	OTS
Bledsoe	AXIOM-D	569.99	Steel-reinforced aluminum	Dynamic tibial mechanism, migration preventing strap system	High impact activities	Both
			Lightweight magnesium material	Dynamic tibial mechanism, migration preventing strap system	Activities of daily living and athletic activities	Both
	Z-12 D	529.99	Lightweight magnesium material	Dynamic tibial mechanism, lightweight/low profile, migration preventing strap system	Activities of daily living and athletic activities	Both
Breg	Fusion	499.99	Aluminum	AirTech™ frame pads, pivot point strap tabs, ProForm medial structure technology	Activities of daily living and athletic activities	Both
	LPR	489.99	Aluminum	AirTech™ frame pads, truss-shaped frame for high strength-to-weight ratio	Activities of daily living and athletic activities	Both
	X2K	479.99	Aluminum	Diamond design for varus–valgus stiffness	Activities of daily living and athletic activities	Both
DonJoy	Defiance	899.99	Carbon composite	4-points-of-leverage system™, FourcePoint™ hinge technology	Activities of daily living to high impact activities	Custom
	Armor	549.99	Aluminum	4-points-of-leverage system™, FourcePoint™ hinge technology, steel-reinforced hinge plate	High impact activities and extreme sports	OTS
	FULLFORCE™	524.99	Aluminum	4-points-of-leverage system™, FourcePoint™ hinge technology	Athletic activities	OTS
Össur	CTi®	399.99	Carbon composite	Total support system™, accutrac® hinges, Sensil® padding	Medium to high impact activities	Both
	Paradigm®	402.99	Carbon composite	Flexible subshell, polycentric hinges	Low to medium impact activities	Both
	MVP® contour	402.99	Aluminum	Flexible subshell, accutrac® hinges, sensil® padding	Activities of daily living and athletic activities	OTS
Townsend	Premier	624.00	Carbon graphite	Townsend motion TM5 + hinges, synergistic suspension strap, anti-migration padding	Activities of daily living and athletic activities	Custom
	Air	650.00	Carbon graphite	Townsend motion TM5 + hinges, synergistic suspension strap, anti-migration padding, anti-rotation tibia shell bolster	High impact activities and extreme sports	Custom
	Rebel	549.99	Aluminum	Townsend motion TM5 + hinges, synergistic suspension strap, anti-migration padding	Activities of daily living and athletic activities	Both

OTS Off-the-shelf

[a] For braces with custom and OTS options, pricing for the OTS brace is listed. Prices reported as USD

Results

History of functional bracing for ACL injury

Documented use of knee braces to treat ligament injury and instability goes back to as early as the 1960s, most notably the use of the Lenox Hill brace by American football quarterback Joe Namath following multiple knee surgeries, which was developed by Castiglia and Nicholas [58]. Since that time, multiple brace manufacturers and brace models have been introduced into the market (Table 1; Fig. 1). To date, functional braces from at least nine different manufacturers have been reported on in the literature [10, 13, 15, 19, 76, 82]. Surveys of the AOSSM, which gathered data in

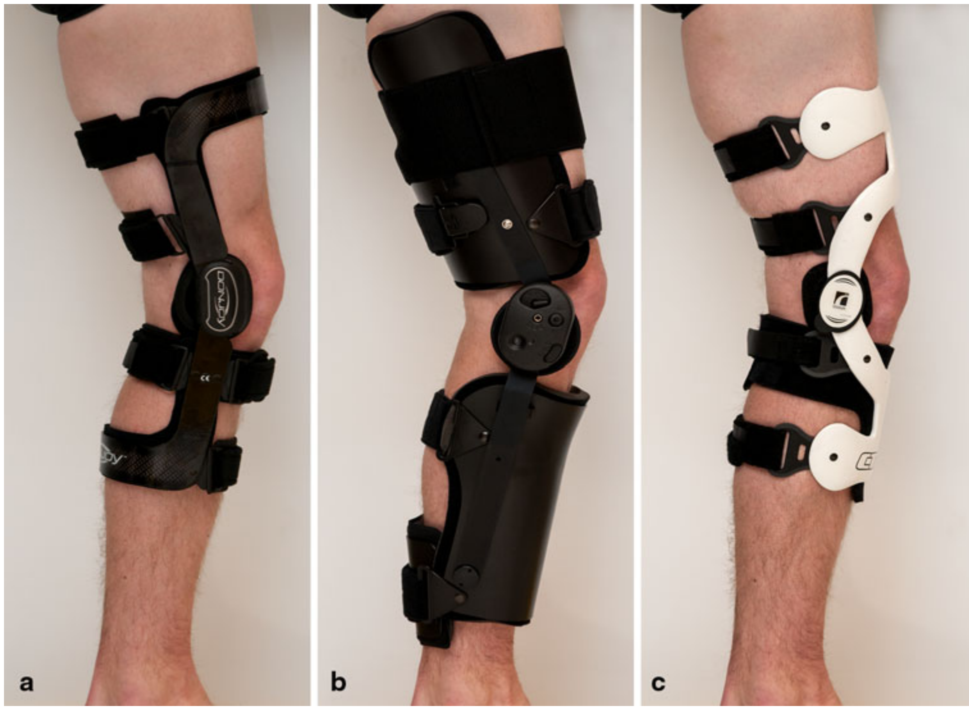

Fig. 1 Photograph of three available functional braces used to treat ACL injury on a right knee, presented in alphabetical order: **a** DonJoy FULLFORCE, **b** Jack ACL Brace, **c** Össur CTi Brace

1993 and 1999, indicate that surgeons are starting to prescribe functional brace use less frequently [23, 24]. This decline corresponds to non-favorable reports on bracing in the literature [15, 54, 63]. Biomechanical studies suggest that existing functional ACL bracing technologies are effective at limiting ATT and strain shielding the ACL graft in response to anterior-directed tibial forces up to 140 N and rotational torques up to 8 Nm [5, 10, 28, 82]. However, the bracing effects diminished in response to higher loads and during athletic activities [5, 13, 19]. Multiple clinical studies have reported that long-term patient outcomes following ACL reconstruction are not measurably improved through the use of a functional brace [15, 54, 63]; however, decreased subsequent injury rates in professional skiers while skiing have been reported [41, 76]. Other reported benefits include improved athletic performance in ACL-deficient athletes, a feeling of heightened stability and confidence in the injured knee while wearing the brace during functional activities, and improved proprioception [15, 18, 19, 54, 85]. The lack of scientific evidence supporting functional bracing has led authors to recommend that surgeons not prescribe functional brace use following ACL reconstruction [15, 54]. While a slight decline in functional brace prescription was reported as of 1999, the use of functional braces to treat ACL injury remains common practice.

Biomechanical characteristics of the native ACL

The purpose of functional ACL bracing is to provide kinematic constraint to the ACL-deficient or reconstructed knee in the absence of an intact ACL, primarily the anterior–posterior (A-P) constraint that the native ACL provides to control ATT, with secondary constraints of internal–external rotation and varus–valgus angulation [1]. The lack of biomechanical and clinical evidence in the literature supporting functional brace use brings into question the design criteria of current brace technologies. No brace has been successfully validated in the literature to appropriately constrain the knee joint and improve patient outcomes. The function of the native ACL should be the foundation of ACL brace design. Therefore, the in situ forces in the native ACL as a function of flexion angle and activity must be defined. The biomechanical characteristics of this ligament have been thoroughly reported on [32]; strain, elongation, orientation, and in situ force behavior of the ACL have been investigated in vivo, in vitro, and with mathematical models of in vivo activities [7, 10, 12, 13, 17, 29, 33, 35, 37–39, 43–46, 52, 64, 67, 69, 71–74, 78, 86, 87].

Several studies from the University of Vermont have reported on the in vivo strain and elongation behavior of the native ACL and ACL graft by implanting a Hall-effect strain transducer or differential variable reluctance transducer onto the anteromedial (AM) substance of the ligament or graft [7, 10–14]. Strain in the instrumented ACL was recorded in response to both manually applied external loads (internal–external tibial torque, anterior tibial force) during weight-bearing and non-weight-bearing conditions and while patients performed various rehabilitation exercises (flexion–extension, squatting, isometric quadriceps contraction, isometric hamstring contraction, co-contraction of the quadriceps and hamstring). Maximum strain was reported to occur at full extension, with decreasing strain as the knee was flexed to 90° [7, 12]. Quadriceps-dominated activities reportedly strained the ACL, while hamstring contraction produced low, if any, strain [5].

The in vivo elongation behavior of the ACL has also been reported with less invasive techniques. Three-dimensional bone models reconstructed from computed tomography scans combined with biplane fluoroscopy bone tracking have been used to visualize tibiofemoral position during walking and weight-bearing flexion [37, 43, 44, 86]. These studies estimated the elongation and orientation of the ACL based on the relative positions of the ACL footprints on the tibia and femur. Maximum elongations of the ACL and its individual bundles during a single leg lunge were reported to occur between full extension and 30° of flexion and decreased with increasing flexion [37, 43]. One study reported that AM bundle length did not change significantly as a function of flexion angle while elongation behavior of the posterolateral (PL) bundle was similar to other studies [44]. During the stance phase of gait, both bundles were maximally elongated at heal strike and late mid-stance and were shortest at toe-off [86].

Several in vitro biomechanical studies have quantified the in situ forces in the ACL in response to external joint loading (anterior tibial force, internal–external tibial torque, varus–valgus torque, simulated pivot shift, simulated muscle loading) using the principle of superposition [29, 35, 38, 45, 46, 52, 64, 87]. Maximum in situ ACL forces were reported to occur between full extension and 30° of flexion, with decreasing force as flexion angle increased. Forces in the AM bundle were reported to be relatively constant, while forces in the PL bundle decreased significantly with increasing flexion [29, 64, 87]. Forces reportedly began to increase again slightly at 150° of flexion [46]. Both co-contraction of the quadriceps and hamstrings and isolated hamstring contraction were shown to decrease force in the ACL compared to isolated quadriceps contraction [45, 46].

In vitro studies are unable to replicate the complexity and magnitude of the loads experienced by the knee joint in vivo. Several studies have developed mathematical models to predict in situ forces during functional activities (walking, chair rise, flexion–extension, squatting, single leg lunge, drop landing) [17, 33, 39, 67, 69, 71–74, 78]. Similar to in vitro investigations, maximum in situ force in the ACL was reported to occur near full extension and decreased with increasing flexion angle. However, predicted in situ forces in the ACL in vivo [33, 35, 39, 67, 69, 71–74, 78] were reported to be up to eight times higher than forces measured in vitro [29, 38, 45, 46, 52, 64, 87].

The reviewed ACL elongation and force data were used in the present study to characterize the in vivo force-flexion behavior of the native ACL during functional activities (walking, squatting, single leg lunge, isometric and isokinetic extension). The A-P component of the ACL force was isolated to quantify the forces which constrain ATT (Fig. 2). This was accomplished using trigonometric calculations and previously described orientation angles of the ACL relative to the tibial plateau [37, 43, 64, 86]. The authors theorize that application of these forces to the knee joint with a functional brace would prevent abnormal translation in ACL-deficient knees and unload the healing ACL graft following reconstruction.

Biomechanical evaluation of functional bracing for ACL injury

Common activities of daily living and rehabilitation exercises are known to induce ATT and strain the ACL [6, 7, 12, 74, 78]. Numerous studies have biomechanically evaluated the ability of functional braces to limit ATT and reduce strain on the ACL or ACL graft [6, 10, 13, 19, 28, 75, 82, 88]. Motion capture and force plate systems have been used to measure the effects of bracing on in vivo knee kinematics and kinetics during functional activities and dynamic cutting and pivoting [19, 75, 82, 88]. Instrumented measurement of ATT and ACL strain in vivo in response to external loads has also been reported [6, 10, 13, 18, 28].

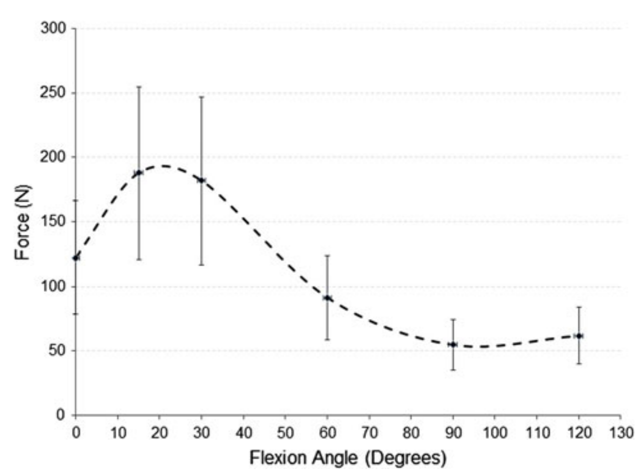

Fig. 2 Graph of the average anterior–posterior in situ force of the ACL in vivo experienced during walking, squatting, single leg lunge, isometric extension, and isokinetic extension

The strain shielding effect of functional bracing has been studied extensively in vivo at the University of Vermont in response to anterior shear loading, internal–external tibial torque, isometric quadriceps contraction, active flexion–extension, and weight-bearing versus non-weight-bearing conditions [10, 13, 28]. Bracing was reported to reduce ACL strain in response to a maximum of both weight-bearing and non-weight-bearing 140 N anterior tibial force and non-weight-bearing 8 Nm internal tibial torques [10, 28]. The strain shielding effect was not significant in response to higher forces, weight-bearing tibial torques, isometric quadriceps contraction, or active flexion–extension.

Similarly, the effect of functional bracing on ATT in ACL-deficient knees has been investigated [6, 18, 82]. Beynnon et al. [6] reported that bracing reduced translation to normal levels in response to a 130 N anterior tibial force during both weight-bearing and non-weight-bearing conditions; however, bracing could not reduce the translation that occurred during the transition from non-weight-bearing to weight-bearing. Contraction of lower extremity muscles combined with functional bracing reportedly reduced translation by 80.1 % in response to a 133 N anterior tibial force, compared to 33.1 % for bracing with muscles relaxed [82]. A similar study reported that bracing decreased ATT in response to a 100 N anterior tibial force, but was unable to limit translation in response to isolated maximal quadriceps contraction [18]. However, these studies lacked the dynamic loading conditions experienced during running, cutting, and pivoting activities.

Cook et al. [19] reported the effect of functional bracing during running and cutting in ACL-deficient subjects. Bracing improved running and cutting performance, but did not prevent abnormal ATT. Subjects reported fewer incidents of subluxation while wearing the brace during testing. Two studies investigated the kinematic and kinetic effects of a functional knee brace with resistance to extension beyond 40° of flexion. Flexion angles and ground reaction forces were analyzed during a vertical stop-jump activity in healthy subjects and during walking, jogging, and stair descent in patients 3.5–6.5 months after ACL reconstruction [75, 88]. Flexion angles were significantly increased while wearing the brace during landing and at initial foot contact during walking, jogging, and stair descent. Ground reaction forces were only reduced during walking. The authors theorized that despite limited changes in ground reaction forces, loads on the ACL would still be reduced due to the increase in flexion angle.

Clinical evaluation of functional bracing for ACL injury

A combination of objective, subjective, and functional evaluations are utilized to evaluate ACL injury and reconstruction. Clinical examinations, such as the Lachman's test and pivot shift examination, are used by physicians to detect ACL injuries by observing differences in anterior and rotational stability compared to the healthy contralateral knee. Restoration of normal side-to-side differences in ATT following ACL reconstruction has often been considered a quantifiable objective measure for successful reconstruction. Studies have used instrumented measurement of ATT with a KT-1000 arthrometer to define clinically significant differences in translation between the injured and contralateral normal knee, with less than 1.5 mm reported as normal, 2.0–2.5 mm considered equivocal, and greater than 3.0 mm of increased ATT indicative of an ACL tear [21, 22]. Insufficient rotational stability has been strongly correlated with functional deficits [89], and a positive pivot shift, which takes into account both translational and rotational stability, has been strongly correlated with poorer subjective scores and functional deficits [40]. Scores calculated from patient surveys, such as the Lysholm, Tegner, IKDC, Cincinnati, and quality of life, are used to subjectively evaluate patient outcomes. Surveys on return to sports, stability during cutting and pivoting, functional performance tests, and giving-way episodes identify functional deficits. While many in vitro studies have reported that various ACL reconstruction techniques have been able to restore anterior and rotational stability to levels not significantly different from the intact state [55, 61, 66, 84], these small and statistically insignificant differences appear to still have clinical implications. This underlines the fact that in vitro biomechanical reports of knee stability are not always predictive of long-term in vivo results. Several clinical studies have evaluated the long-term effects of functional bracing following ACL reconstruction using objective, subjective, and functional patient outcome measures [15, 18, 54, 63, 76].

A randomized controlled trial in 2008 compared the effects of functional knee brace and neoprene sleeve use after ACL reconstruction with four-strand hamstring tendon grafts [15]. One hundred and fifty patients were randomized to 1 of the 2 groups 6 weeks postoperatively and evaluated at 6, 12, and 24 months postoperatively. The metrics included an ACL quality of life questionnaire, side-to-side differences in ATT, single limb forward hop test, and Tegner activity level. Patients were prescribed either a functional ACL knee brace (DonJoy Legend, DJO Global Inc., Vista, CA) or an open patella neoprene sleeve (Neoprene Knee Sleeve, DJO Global Inc., Vista, CA). No significant differences were observed for any of the outcome measures between the brace and sleeve groups after 1 and 2 years. Self-reported patient compliance for wearing the brace was 63 % at 6- and 12-month follow-up, compared to 65 % for the sleeve group. Improved confidence in the knee and assistance returning to sports activities was rated higher for the brace group than the sleeve group at 12-month follow-up. The authors concluded that use of the functional knee brace did not improve any of the ACL-specific outcome measures when compared to neoprene sleeve use.

One hundred volunteers from 3 of the US service academies were randomized between braced and non-braced groups following ACL reconstruction with BPTB grafts and evaluated on prone heel height differences, side-to-side differences in ATT, Lachman's test scores, pivot shift examination scores, Lysholm scores, single leg hop test, IKDC scores, range of motion, and isokinetic strength after a minimum of 2 years postoperatively [54]. Braced patients were prescribed an off-the-shelf functional knee brace to be worn daily for 6 months and for all rigorous activities for at least 1 year. At 2-year follow-up, no significant differences were observed between the braced and non-braced groups. Seventy-nine percent of patients reported being compliant with prescribed brace use. Patients reported confidence in the knee while wearing the brace but complained about fit, slippage, and negative effects on athletic performance. The authors concluded that functional knee bracing after ACL reconstruction did not influence patient outcomes in a young, active population.

In a 1999 study by Risberg et al. [63], the effect of knee bracing after ACL reconstruction with BPTB grafts was evaluated at 6 weeks, three and 6 months, and one and 2 years follow-up. Sixty patients were randomized into one of two groups. Braced patients wore a rehabilitation brace (Range of Motion Brace, DJO Global Inc., Vista, CA) for 2 weeks and then a functional knee brace (DonJoy Gold Point, DJO Global Inc., Vista, CA) for the next 10 weeks. The brace was then worn as needed for physical activity. Outcome measures included side-to-side differences in ATT, Cincinnati knee scores, range of motion, Tegner activity level, muscle atrophy, muscle strength, and functional knee testing. The Cincinnati knee score for the braced group was significantly improved compared to the non-braced group at 3 months. However, no significant differences were observed at any other follow-up times. Significantly increased muscle atrophy was observed for the braced group after 3 months, but did not differ significantly after 6 months. No other differences were reported. Seventy-six percent of patients reportedly complied with the recommended brace use for the first 3 months and 62 % of patients continued to use the brace for sports activities beyond 3 months. Braced patients reported improved function and decreased giving-way episodes during sports activities. Lack of compliance was associated with discomfort caused by the brace. The authors concluded that, with the exception of improved Cincinnati knee scores and increased muscle atrophy after 3 months, this functional knee brace had no effect on patient outcomes following ACL reconstruction.

Functional brace use has been reported to decrease the rate of subsequent injury to both the ACL reconstructed and ACL-deficient knee in skier populations [41, 76]. A study in 2006 [76] evaluated the effect of functional brace use on rates of subsequent knee injury during skiing in a population of professional skiers who had undergone ACL reconstruction with BPTB or hamstring grafts at least 2 years prior to the current ski season. Eight hundred and twenty subjects were included in the study who had undergone ACL reconstruction, two hundred and fifty-seven of whom wore a functional brace (CTi2, Innovation Sports, Irvine, CA) while skiing. Sixty-one subsequent injuries were reported. The injury rate for braced skiers (4 %) was significantly lower than non-braced skiers (9 %). The rate of injury requiring surgery was significantly higher for the non-braced group (4 %) compared to the braced group (1 %). Eleven injuries, all in the non-braced group, required ACL reconstruction. Patient compliance with recommended brace use was not evaluated. The authors concluded that skiers with a reconstructed ACL without a functional brace were almost three times more likely to experience a subsequent knee injury than braced skiers.

A similar study in 2003 [41] reported on the effect of functional brace use on the rate of subsequent knee injury in ACL-deficient skiers. One hundred and eighty ACL-deficient professional skiers were included in this study, and one hundred and one skiers were prescribed a functional brace (CTi2, Innovation Sorts, Irvine, CA) based on shared doctor–patient decision making. The injury rate for non-braced skiers (13 %) was significantly higher than for braced skiers (2 %). Patient compliance was not monitored. Non-braced ACL-deficient skiers were reportedly over six times more likely to sustain a subsequent knee injury than ACL-deficient skiers who wore the brace.

Discussion

The major findings in the current review are:

- Functional bracing of ACL injuries is commonly practiced and imposes a significant financial burden on the healthcare system.
- Biomechanical literature demonstrates that functional bracing does not strain shield the ACL or reduce ATT in response to anterior forces and internal torques greater than 140 N and 8 Nm, or during functional activities.
- Clinical literature demonstrates that use of a functional brace postoperatively following ACL reconstruction does not affect long-term patient outcomes.

- Clinical evidence suggests functional bracing of ACL reconstructed and ACL-deficient knees prevents subsequent knee injury during skiing.
- Patient compliance with prescribed functional brace use has been limited by brace discomfort, slippage, fit, and inhibition of athletic performance.
- This review supports the need for improved functional brace design to account for the dynamic, flexion angle–dependent forces that the ACL has been reported to experience in vivo.

The purpose of a functional ACL brace is to provide the ACL-deficient or reconstructed knee with normal stability in the absence of a healthy ACL; specifically to prevent abnormal ATT and excessive strain and elongation of the ACL graft. Our review of the ACL biomechanical literature demonstrates that the ACL is a dynamically loaded ligament that experiences varying levels of force as a function of flexion angle and activity. These findings may explain why current bracing technologies, which do no replicate the loading characteristics of the native ACL, have been reported in the literature to be unsuccessful.

The results of the biomechanical literature on functional bracing are mixed, with reported reductions in ATT and strain on the ACL but diminished effects beyond anterior forces and internal torques of 140 N and 8 Nm. Additionally, bracing reportedly improved running and cutting performance, decreased subluxation and giving-way episodes, and increased knee flexion angles during dynamic activities, but was unable to reduce ATT and ground reaction forces. The reviewed biomechanical evidence suggests that the stabilizing effects at time zero of current bracing technologies are insufficient. Additionally, the use of a functional brace following ACL reconstruction is not supported by reported long-term patient outcomes. A positive prophylactic effect was reported in professional skiers with ACL-deficient and reconstructed knees, and patients commonly reported feeling more stable and confident in the injured knee while wearing the brace during functional activities. However, significant improvements in clinical outcomes following ACL reconstruction were not reported. Based on the reviewed scientific evidence, the authors recommend that current functional bracing technologies not be used postoperatively following ACL reconstruction. The reported effects of functional bracing during athletic activities were more positive. Therefore, functional bracing should be used by ACL-deficient or reconstructed patients during sports activities, especially during skiing and other cutting activities.

Although current bracing technologies have been reported to be largely ineffective, the need to provide normal stability to the ACL injured knee is still apparent. Graft failure and elongation, residual instability, functional deficits, secondary ACL injury to both the injured and contralateral knee, and inability to return to sports and prior level of play remain common [2–4, 20, 27, 34, 52, 53, 60, 65, 68, 80]. Anatomic reconstruction techniques have optimized placement of the graft tunnels to more closely replicate the native anatomy of the ACL; however, anatomic tunnel placement reportedly increases the force placed on the graft compared to non-anatomic reconstructions [61, 66] and may increase the risk of failure [80]. Additionally, rehabilitation protocols are placing higher demands on the graft as patients are returning to range of motion, weight-bearing, strength building, and sport-specific exercises faster than ever before [9, 70, 81]. Patients with ACL injury who opt to not undergo surgical intervention or postpone the surgical treatment, as has been recommended in children, are faced with functionally disabling instabilities, increased risk of subsequent injury to the joint, and increased risk of early onset osteoarthritis [6, 8, 9, 18, 42, 77].

No existing functional ACL brace has been successfully validated in the literature to restore normal anterior stability to the ACL-deficient knee and improve long-term patient outcomes following reconstruction. The ideal functional brace to treat ACL injuries should replicate the constraint of the native ACL on the knee joint. Specifically, the brace should apply a posterior-directed force to the anterior proximal tibia that varies with flexion angle, as described in the present manuscript. Additionally, the magnitude of the force should be adjustable to account for the activity being performed. Other brace design requirements should address increasing patient compliance with improved comfort, fit, and decreased slippage, as well as considering decreased inhibition of sports performance.

Conclusions

The reviewed biomechanical and clinical evidence on functional bracing of ACL injuries does not support the use of current bracing technologies. To appropriately control ATT and prevent elongation of the ACL graft during functional activities, a brace designed to reproduce the forces of the native ACL on the knee joint should be pursued.

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Conflict of interest The authors declare they have no conflict of interest.

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