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A historical perspective of PCL bracing

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Abstract

Purpose Currently there are many functional knee braces but very few designed to treat the posterior cruciate ligament (PCL). No PCL braces have been biomechanically validated to demonstrate that they provide stability with proper force distribution to the PCL-deficient knee. The purpose of this review was to evaluate the history and current state of PCL bracing and to identify areas where further progress is required to improve patient outcomes and treatment options.

Methods A PubMed search was conducted with the terms "posterior cruciate ligament", "rehabilitation", "history", "knee", and "brace", and the relevant articles from 1967 to 2011 were analysed. A review of the current available PCL knee bracing options was performed.

Results Little evidence exists from the eight relevant articles to support the biomechanical efficacy of nonoperative and postoperative PCL bracing protocols. Clinical outcomes reported improvements in reducing PCL laxity with anterior directed forces to the tibia during healing following PCL tears. Biomechanics research demonstrates that during knee flexion, the PCL experiences variable tensile forces. One knee brace has been specifically designed and clinically validated to improve stability in PCL-deficient knees during rehabilitation. While available PCL braces demonstrate beneficial patient outcomes, they lack evidence validating their biomechanical effectiveness.

Conclusions There is limited information evaluating the specific effectiveness of PCL knee braces. A properly designed PCL brace should apply correct anatomic joint forces that vary with the knee flexion angle and also provide adjustability to satisfy the demands of various activities. No braces are currently available with biomechanical evidence that satisfies these requirements.

Level of evidence IV.

Keywords Posterior cruciate ligament · Brace · Functional · Rehabilitation

Introduction

What are the available posterior cruciate ligament (PCL) bracing options that have been validated for patients with PCL injuries? Immediately following the first cruciate ligament reconstruction performed by Mayo Robson in 1903, it is unlikely that a stability brace was available to the patient during healing and rehabilitation [22]. However, significant advances in orthopaedic care and treatment have occurred since then and today there are a plethora of options for functional knee braces. Despite the wide variety of functional braces available, very few cater specifically to the stability of PCL, which is the main provider of resistance to posterior translation of the tibia relative to the femur [13]. None of the PCL braces available have been biomechanically evaluated to demonstrate that they provide proper force distribution to the knee, but one brace currently exists with clinical evidence reporting improvements in patient outcomes [17].

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While numerous options exist for functional bracing of the anterior cruciate ligament (ACL), the large variety of brace functions and specifications to fit an ACL-injured patient's needs do not exist for the PCL-injured patient. Injuries to the ACL occur in approximately 80,000 individuals per year in the United States, creating the large market for ACL braces [12]. Historically, research on knee ligament injuries has focused on the ACL, perhaps due to the greater number of ACL versus PCL injuries per year. The incidence of PCL tears in acute traumatic knee injuries is associated with 3–37 % of all knee injuries [13]. This is certainly a large range and is difficult to quantify or validate an accurate estimation of the number of PCL injuries in patients. The percentages reported are accurate based on the methods used to diagnose knee injuries but vary heavily depending on the group or surgeon's specialty due to differences in patient population. For example, an orthopaedic surgeon who mostly treats athletes will tend to see a lower incidence of PCL tears, while a trauma surgeon who treats individuals in an emergency room with high-velocity injuries will see a higher rate of PCL injuries [8].

The PCL has been reported to suffer more partial tears than the ACL, and isolated grade I-II PCL injuries have been reported to have a high potential for good clinical outcomes following nonoperative treatment [2, 3, 4, 6, 15, 16, 19, 28, 29]. Due to these healing capabilities, a grade I–II PCL tear has the potential for satisfactory healing in a properly reduced knee joint.

We have reviewed the history of PCL bracing from the first functional Lenox Hill derotation knee brace to the current options available today [3]. An overview of the analysis of the PCL with respect to biomechanical function, degree of injury, rehabilitation and bracing options to provide stability to the injured PCL knee joint follows. The purpose of this review was to evaluate the history and current state of PCL bracing and to identify areas where further progress is required to improve patient outcomes and treatment options.

Materials and methods

A literature search was performed using the PubMed MEDLINE database (PubMed) with combinations of the keywords "posterior cruciate ligament", "rehabilitation", "history", "knee", and "brace" (www.ncbi.nlm.nih.gov/pubmed). Searches also included rehabilitation procedures and clinical outcome studies for patients undergoing nonsurgical rehabilitation and surgical procedures to repair or reconstruct the PCL. The biomechanical considerations and properties of the PCL were analysed through a keywords literature search to elucidate the characteristics a knee brace should have pertaining to the PCL. Further relevant publications were obtained and analysed, which were found from the reference sections of the initially identified manuscripts. A review of the past and current knee braces available to patients was performed to determine the braces available to PCL-injured patients and identify any research attempting to biomechanically or clinically validate the existing options. The rehabilitation protocols and options for PCL-injured patients were reviewed.

Results

History of knee bracing for PCL deficiency

When performing an English language literature search in PubMed, in October of 2011, there were 64 results when searching for "posterior cruciate ligament and brace". Of these results, 8/64 articles focused on outcomes specifically associated with utilizing a PCL brace on an injured PCL knee. Of these eight articles, five were relevant to the history of PCL bracing. When performing a literature search for "posterior cruciate ligament and brace and history", two articles were found, neither of which was relevant to PCL bracing.

Very few knee braces have been specifically developed to ensure stability in PCL-injured knees. Often, knee braces that have been developed for general knee instability or an ACL injury have been adapted to function as PCL braces. One of the earliest examples of a functional knee brace was the Lenox Hill derotation brace [36]. This brace was developed to treat chronic knee instability resulting from any ligament deficiency, including PCL insufficiency. Today, the single clinically validated PCL-specific brace available is the PCL-Jack brace (Albrecht, Stephanskirchen, Germany), which provides support to the PCL-injured knee following an injury [17].

Biomechanical characteristics of the posterior cruciate ligament

One of the main reasons for the lack of focused attention on research of the PCL is due to its decreased incidence of injury compared to the ACL. This decreased injury incidence is perhaps in part due to the strength of the PCL relative to the ACL. One of the first studies regarding PCL strength reported the PCL to have twice the ultimate tensile strength of the ACL while the stiffness values of the two ligaments were shown to be similar [22]. Further understanding of the biomechanical characteristics of the PCL could lead to improved PCL brace design.

Recent studies have reported the position, length and load of the PCL during dynamic testing on human knees with magnetic resistance imaging (MRI) biplane studies

[5, 7, 18, 23, 27]. Their results demonstrate the attachment sites, elevation and deviation angles with respect to three-dimensional space, the amount of twisting and the length of the PCL during the dynamic lunges and squats. When considering the knee to be a mechanical model, a ligament can be modelled as a tension spring. If the length of the ligament increases, there is greater tension on the ligament and thus more force exerted on the ligament by the surrounding anatomy. The results of these MRI studies demonstrated consistent findings that the length of the PCL increases when the knee is under load as it flexes from 0° to 90° of flexion [5, 7, 18, 23, 27]. Additional studies found the same trend and then further reported that the PCL length was relatively constant from 105° to 120° of flexion and then decreased in length from 120° to 135° of flexion [18, 27]. Biplane studies demonstrate that during dynamic activities, there is a consistent and variable change in the length of the PCL relative to the knee flexion angle.

Another study estimated the in vivo forces on the cruciate ligaments during dynamic motions [7]. This study used a combination of motion analysis and electromyography of the leg muscles as inputs into a biomechanical knee model to estimate the forces produced on the PCL. Forces were calculated during two motions while the subject was holding dumbbell weights: a forward and a side lunge. The results of the study reported PCL forces to be between 205 Newtons (N) and 765 N during these activities. Significantly higher loads were reported at the higher knee flexion angles of both the descent and ascent portion of the forward and side lunges than at the lower flexion angles. The forward lunge reported consistently higher forces on the PCL than the side lunge [7]. While the accuracy of this study is dependent upon the accuracy of the model, it provides an estimate of the nominal in vivo loads that could be exerted on the PCL during heavy athletic activities. The results clearly demonstrate trends of changing force on the PCL relative to knee flexion angles.

Cadaveric testing has defined the in situ forces on the PCL [10, 11, 14]. Using the principle of superposition with a six degree-of-freedom robot (DOF), the forces on the PCL with various posterior drawer loads over a range of knee flexion angles have been reported. The forces on the anterolateral and posteromedial bundles were measured and when combined, a variable increase in the PCL force was observed from 0° to 90° of knee flexion [10]. With an applied 110 N posterior tibial load, the forces on the PCL increased from an average of 35 N at 0° of knee flexion up to 112 N at 90° of knee flexion [10]. Harner et al. [14] measured the in situ PCL forces using a 134 N posterior tibial load and reported that the forces increased from 30 to 127 N from 0° to 90° of knee flexion and decreased to 108 N at 120° of knee flexion.

The PCL forces were also measured by Markolf et al. [25] with 16 human cadaveric knee specimens where the femoral PCL-attachment site was cored out and then connected to a load cell. This direct measurement reported the forces on the PCL while a posterior tibial load was generated by a six DOF robot throughout a 0°–120° range of motion. As the knee was flexed from 0° to 5° of flexion, the force on the PCL decreased. Then, the force on the PCL increased in a nonlinear nature as the knee was flexed up to 105° of flexion. Finally, the force decreased in a nonlinear nature as the knee was flexed to 120° of flexion [25]. The results demonstrated that the PCL had a variable tension throughout the range of motion (Fig. 1). In summary, biomechanical research reports a consistent trend with tensile forces on the PCL varying with knee flexion. This is valuable information that should be incorporated into future brace designs.

Clinical characteristics of the posterior cruciate ligament

Gravity and the dynamic loads from the hamstrings provide a posterior force onto the tibia when a patient is lying relaxed in the supine position, causing the so-called posterior sag sign [24, 34]. If knee joint positioning is not properly controlled during rehabilitation and healing, these forces can cause the PCL to heal in an elongated position, resulting in long-term joint instability [19, 31]. With properly controlled joint position, however, such as that provided by a brace that applies an anterior force directed to the posterior proximal tibia, this issue has been reported to be improved. The brace used by Jacobi et al. [17], the PCL-Jack brace (Fig. 2a), has fifteen levels of manual adjustment, each of which reportedly provides a constant spring-loaded anterior force to the tibia. The constant force

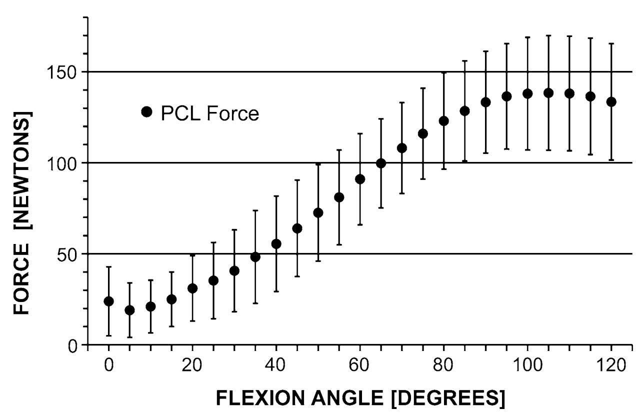

Fig. 1 Graph of the in vivo PCL forces versus knee flexion angle with a 100 N posterior tibial force in 16 cadavers as measured with a bone cap and force transducer in a robot, reprinted with permission from Arthroscopy [25]

Fig. 2 Photograph of examples of available PCL Knee Braces shown on a right knee: **a** PCL-Jack Brace, **b** Ossur CTi brace with static PCL strap addition, **c** DonJoy Armor brace with static PCL strap addition (photo credit: Joe Kania)

applied to the tibia for each level of the brace reportedly does not change throughout the 0°–90° range of motion that the brace allows. The benefit and effect that this brace produces is the force to counteract the posterior sag of the tibia. A clinical validation study performed with this brace demonstrated a significant improvement in bilateral comparative Rolimeter arthrometer (Aircast; DJO, Vista, California, USA) measurements. The patients wore the brace for the first 4 months following their injury and improved from an average of 7 mm of initial posterior sag to 2 mm of posterior sag 12 months later [17]. This brace was also utilized in a rehabilitation protocol for 6 months following a double bundle PCL reconstruction for grade-III PCL tears (both isolated and combined) in 31 patients [33]. The operative technique and rehabilitation resulted in an average PCL stress radiograph improvement from 15.0 mm preoperatively to 0.9 mm at an average of 2.5 years postoperatively when compared to the contralateral knee [33]. While all patients were noted to be compliant with PCL brace wear in this study, brace wear compliance has not been demonstrated well in other studies.

Two other studies reported on the benefit of applying anterior forces to a tibia during PCL healing to restore normal tibiofemoral position [1, 19]. Ahn et al. [1] reported on 38 patients with acute isolated PCL tears who underwent the same rehabilitation protocol with an average follow-up of 24 months. Their rehabilitation included a long-leg cast with an anterior force directed to the tibia while at full extension for 3 weeks. Upon removing the cast, a brace applying an unknown static spring-loaded anterior force to the posterior proximal tibia was worn for another 6 weeks. Posterior tibial translation was measured with a KT-1000 arthrometer (MEDmetric, San Diego, CA, USA), and results were reported from the initial evaluation and the most recent follow-up evaluation (average of 51.7 months post-injury). Sixteen patients with grade I injuries improved from 4.5 mm of posterior tibial translation to 3.8 mm, and seventeen patients with grade II injuries significantly improved from 7.9 to 5.9 mm [1]. This study shows the ability of an anterior force to counteract posterior sagging immediately following a PCL injury to improve PCL healing and to reduce, but not resolve, residual position knee laxity. Jung et al. [19] followed a similar protocol using long-leg casting with an unspecified anterior force for 6 weeks followed by a spring-loaded anterior force PCL brace for 6 weeks in 17 subjects. Improvement was reported in mean side-to-side difference as measured by a KT-1000 arthrometer from 6.2 mm prior to immobilization to 3.0 mm at the most recent follow-up (minimum of 2 years post-injury). Overall, improved clinical outcomes have been reported following PCL injuries by applying anterior directed forces to the tibia during PCL healing to reduce PCL laxity. A clinical recommendation has been summarized for PCL brace wear for patients with isolated PCL injuries (Table 1).

Rehabilitation of the posterior cruciate ligament injury

While the use of braces in the rehabilitation of PCL injuries largely lacks supporting evidence, clinicians recommend that patients with PCL injuries use PCL braces [13]. In performing a PubMed search using keywords "posterior cruciate ligament and rehabilitation and brace", 31 publications were identified. Of these results, 8/31 articles were relevant because they used bracing strategies during rehabilitation of PCL injuries. While the rational for bracing may be varied due to different patient needs, typical reasons for PCL bracing include: to protect the reconstructed PCL and prevent graft elongation (rehabilitative), to assist PCL healing in nonoperative cases (rehabilitative), to provide external stability to a PCL-deficient knee (functional), or to mitigate the development or progression of osteoarthritis in the PCL-deficient knee (prophylactic).

The use of rehabilitative bracing in postoperative care follows various protocols. Publications have reported rehabilitation methods using a long-leg knee brace locked in extension, or the use of an immobilizer with or without a foam cushion for anterior tibial support, for the first

Table 1 Recommended guidelines for use of a dynamic PCL brace for isolated PCL tears

Phase (weeks)	Brace use
Acute (0–6)	At all times, except to shower and change clothes
Subacute (7–12)	At all times, except to shower and change clothes
Chronic (>12)	Cases of fixed posterior translation (primarily for preoperative treatment)

4–6 weeks postoperatively to prevent posterior tibial sag [9, 30, 35]. While use of this bracing protocol may be widespread, little evidence exists to support the biomechanical efficacy of either of these bracing methods. Additionally, the duration of bracing appears to follow soft tissue healing rather than ligament maturation timelines. It has been reported that it takes 6 weeks for early biological healing of soft tissues from repairs and reconstructions to occur, so care must be taken to avoid loading the PCL repair or reconstruction soon after surgery [13]. For this reason, PCL brace wear is believed to be most successful when used for the first 6 weeks after injury or post-surgically. In the authors' experience, use of a PCL brace may alleviate a fixed posterior translation of the knee, but it has not been found to restore joint stability. Another approach to protect the PCL postoperatively is to use a PCL brace for 6 months following double bundle PCL reconstruction as previously described [33]. Good to excellent functional results have been demonstrated in nonoperative PCL patients treated with a PCL-Jack brace for a 4-month duration [17].

The use of return to sport (functional) braces has largely been based on the surgeon and physical therapist's personal preferences. In ACL reconstruction, many patients report an increased sense of postural stability with brace use postoperatively; however, these results have not been validated in a PCL-deficient patient population [26]. The PCL-Jack brace, while providing the tibia with constant anterior force, is too bulky and restrictive of full range of motion to be practical for everyday use or use in sports activities. For patients who desire to have a near full range of motion, PCL braces exist that provide a posterior directed force on the proximal femur and an anterior directed force on the proximal tibia through static straps. The Ossur CTi (Fig. 2b) and DonJoy Armor (Fig. 2c) braces are among several similar products developed by various bracing companies that use static strapping strategies to attempt to provide stability. In theory, the forces provided by these functional braces prevent knee instability due to an injured PCL, but there currently are no clinical or biomechanical studies that validate their effectiveness. In the authors' experience, some difficulty and instability occur in rapid descending or deceleration activities for patients while using these functional braces.

In theory, the application of a prophylactic brace that applies an anterior force to the posterior proximal tibia should allow for a normalization of the joint contact forces, and a reduction in the rate of osteoarthritis development [32]. Unfortunately, no evidence currently exists to support this theory. The development of patellofemoral and medial compartment osteoarthritis in chronic grade-III PCL tear patients treated nonoperatively is well recognized [15]. Strobel et al. [34] reported that after 5 years of a PCL deficiency, 78 % of patients showed medial femoral condyle articular cartilage degeneration. Until bracing technology and research progresses, it is unlikely that brace use will be proven to be effective in limiting osteoarthritis development in the PCL-deficient knee.

Discussion

The most important finding of this review is that there currently is limited information evaluating the specific effectiveness of a PCL knee brace. Based upon our review of the literature, the purpose of a PCL brace should be to provide functional stability to a knee joint for either an acute injury to improve the healing potential of a torn PCL or to postoperatively protect a PCL reconstruction graft. There are very few clinical trials reporting the effectiveness of PCL rehabilitation that includes bracing, and these studies do not specifically note "why" or validate "how" the brace used works. These studies also would have benefitted from a control group of patients who underwent rehabilitation without casting or bracing in order to compare the outcomes between the groups. Additionally, bracing the PCL-injured knee to mitigate the development of osteoarthritis or to allow individuals with PCL-deficient knees to return to sport with nonoperative treatment may also be future indications for a PCL knee brace. However, no biomechanical evidence exists to suggest that current PCL braces are capable of achieving these outcomes.

The detailed biomechanical studies reported on in this review have demonstrated the dynamic changes in force on the PCL during knee flexion and provide evidence as to why the currently available static PCL braces are ineffective at applying correct anatomic loads. These studies have reported that the PCL is in tension during knee motion to provide reaction forces anteriorly on the proximal tibia and posteriorly on the proximal femur and that this tension on the PCL changes based on the knee flexion angle. These anatomic forces applied to the knee by the native PCL should be reproduced by a PCL brace in the PCL-injured patient. For example, a PCL brace applying correct anatomic loading could be very helpful in stabilizing the knee for decelerating or descending activities. Biomechanical evaluation of the forces on the PCL during active motion has demonstrated a significant increase in the force on the PCL during posterior tibial translations and applied posterior tibial forces, such as the forces that are experienced in decelerating or descending activities. In order to provide correct anatomic loading and support during these types of manoeuvres, an ideal brace should reproduce and accommodate for changes in PCL loading through the full range of motion of the activity. The static PCL braces currently on the market provide the same load throughout the range of knee flexion and thus do not provide ideal support of the knee joint during these types of activities.

Today, most PCL knee braces are fabricated and adapted from existing ACL braces with modifications to the strap positioning configurations. The one exception is the PCL-Jack brace, which has been demonstrated to be effective in supporting the tibia with a constant anterior load. This brace, however, limits the patient to 0°–90° of knee flexion; thus, it is considered a rehabilitation brace and was not designed for sports performance. This is not useful for a patient seeking a brace for long-term use or for an athlete with a PCL injury looking for a stability brace to allow a return to sports participation. An ideal functional PCL brace would need to accommodate the larger range of motion necessary for sports participation and be sufficiently low profile enough to allow ease of movement on the sports field.

It is the authors' opinion that nonoperative and postoperative management of PCL injuries should incorporate the use of a dynamic brace that supplies a constant anterior tibial force for 4–6 months. This will protect the PCL by off-loading the forces that would have been applied to the healing PCL. Considering the intended reason for using a PCL brace-effectively acting in place of the natural PCL anatomy-the forces a PCL-specific brace should apply to the knee should be similar to the forces a healthy, intact PCL would otherwise apply on the knee joint through reactive forces. Following an injury, as the PCL heals, the brace could slowly and safely reduce the external forces applied to the joint to allow the native PCL to slowly increase the internal joint reaction loads applied within the knee. In an injured knee, anatomic remodelling occurs through a process called mechanotransduction, where cells sense and respond to mechanical loads [20]. Thus, wearing a PCL brace may be more beneficial than wearing an immobilizer following an injury. Slowly stressing the ligament over time as it is healing should allow it to regain strength at a safe rate.

The results of the biomechanical literature search suggest that a PCL brace would ideally apply an anterior force to the posterior proximal tibia and a posterior force on the anterior proximal femur. The nominal load applied by the brace should change based on the knee flexion angle. The brace should also have adjustability to change the magnitude of the nominal load for the activity being performed. For example, lying supine will require less force than walking, which requires less force than running or squatting. In the absence of biomechanical evidence validating the loads applied to the knee by PCL braces, however, brace use is likely to remain subject to clinician preference. Further research into this topic is necessary to validate the use of a dynamic PCL brace to avoid previous failed historical attempts at PCL bracing, such as olecranization of the patella [21].

Conclusions

In conclusion, this review suggests that in order to best support the PCL-injured knee joint, a properly designed PCL brace should apply a force that varies with knee flexion angle to mimic the anatomic forces applied by the PCL in the healthy, intact knee. There is currently no brace available with biomechanical evidence that satisfies these requirements.

Currently, the main conclusions to be drawn for the effectiveness of a PCL brace are from clinical trials that report improvement in objective and subjective criteria with regards to the patient's knee function and comfort level when performing various activities. Further research is needed for biomechanical and clinical validation of knee braces' effectiveness with regards to supporting a knee with a grade I, II or III PCL injury or following a PCL graft reconstruction. Future biomechanical and clinical studies should evaluate PCL brace effectiveness with respect to the forces provided at varying knee flexion angles to ensure proper anatomic support is being provided.

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