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REVIEW

Ten questions in sports engineering: knee brace efficacy for sports injuries

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Abstract
With growing support for more active healthier lifestyles, focus on injury prevention and treatment solutions is rising. One debated topic is the use of knee braces for knee injuries. Evidence and clinical recommendations in preventing and treating knee injuries have changed with the development and refinement of knee braces. Given the various knee braces available, this paper explores potential opportunities and recommendations for future research. The ten questions paper examines the use of braces and the relationship between user experience, design and performance. It further explores challenges and issues associated with knee braces. It offers a fresh perspective into redesigning braces with the latest innovations in materials and sensors. Through these questions, we hope to offer a fresh perspective on knee bracing and advance understanding of future opportunities to improve knee brace design.

Keywords Design · Materials · Injuries · Treatment · Range of motion (ROM) · Biomechanics

1 Introduction

Knee braces have become increasingly popular worldwide, due to a rise in sports-related injuries, an ageing population and advancement in brace technology [1, 2]. The global knee brace market is projected to reach $2.6 billion by 2031 [3]. Knee injuries are more prevalent in females, particularly those to the anterior cruciate ligament (ACL), often resulting in substantial and long-lasting impact on their lives and careers [4]. Knee braces are often used to provide support and stability to the knee joint in managing these injuries. Despite their widespread use, commercially available knee braces, such as those provided by the UK's National Health Service (NHS), are often off-the-shelf designs that are not tailored to the individual's needs [5]. This approach tends to overlook the variations in anatomical shape and morphology amongst individuals, including sex differences. Although the knee brace market has grown, there remains a need for greater awareness and understanding of the underpinning technology to ensure optimal use and effectiveness in injury management and recovery. Here we address ten key questions to highlight differences between knee braces, why they are used, key challenges faced by users and opportunities for research and improvement.

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2 Question 1: what are knee braces and why are they used?

International Standard Organisation (ISO) 9999:2022 specifies a classification and terminology for assistive products as 'designed to optimise functioning and reduce disability'. Knee braces fall within this standard, under the category of orthoses for lower limb, devices that are applied externally to modify the structural and functional characteristics of the

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neuromuscular and skeletal system [6]. The general use of knee braces is to manage chronic conditions like osteoarthritis (OA), rheumatoid arthritis (RA), and acute injuries (ligament sprains and ruptures). Knee braces are commonly used to support and stabilise the knee joint for all these conditions. They are also worn to reduce injury risk.

Sport is a commonly cited cause of lower limb injuries. Anatomy, environment and hormonal and neuromuscular factors can influence knee injury risk [7, 8]. Individuals describe knee injuries as debilitating, with joint pain varying from mild to constant and deep, often affecting their range of motion (ROM) [9]. For athletes, these injuries can be career and life-changing, with short- to long-term effects (re-injury risk) and substantial personal and financial impact. Elite athletes sometimes wear knee braces as a precautionary measure to prevent injuries, especially in contact sports [10, 11].

Whilst knee injuries and treatments are documented in the literature [12, 13, 14], the effectiveness of knee braces is debated. There is concern about the inconsistent and insufficient objective data available for knee braces being marketed [15]. Greater evaluation of the effectiveness of knee braces is required, enabling more informed decision-making by both users and health professionals.

3 Question 2: what are the different types of knee braces?

Modern knee braces originated in the 1960s [16] and have since developed with advances in biomechanics, medicine and engineering [17]. With increased use and development of knee braces, it is hard to keep abreast of all available offerings. Most knee braces are designed to address various knee pathologies, often sustained during sport, to provide targeted support and stabilisation for conditions such as ligament injuries, and patellofemoral disorders and to reduce the risk of onset osteoarthritis from an injury. Clinical guidelines from the American Academy of Orthopaedic Surgeons (AAOS) classify knee braces by what they are designed to do; injury prevention, joint stability, rehabilitation support, or patellar alignment, to guide appropriate selection based on injury needs [18, 19]. They are split into four main categories: (1) prophylactic, (2) functional, (3) rehabilitation and (4) patellofemoral. [20] (Fig. 1). These classifications are not universal but are widely used. Although this classification system remains influential, it does not account for brace types like unloader braces for osteoarthritis or "smart" braces with embedded sensors, which emerged after the AAOS guidelines were written.

Knee braces can be further classified into two groups: ready-made (off-the-shelf) and custom-made. Ready-made braces typically range in size from small, medium to large, although these sizes are not universal. They provide a non-bespoke fit at a lower cost than a custom-made brace which

Fig. 1 Photos showing an example of a knee brace from each of the four categories of the AAOS classification system [20]. Braces are fitted to a mannequin leg and are arranged from left to right in order of increasing complexity (Author's own image)

is specifically designed or adapted to fit the user's knee [21]. Manufacturers of ready-made knee braces typically expect users to measure their knees and surrounding areas to ensure a proper fit [22]. This means the fit of ready-made braces may be subject to human error, misinterpretation or inconsistencies during the measurement process.

Despite the varied knee brace types offered for different conditions, an overlooked aspect in research is the understanding of the relationship between brace design and knee injury. Braces designed for injury recovery often differ in structure and function from those intended for injury prevention. There is a need to update and standardise the categorisation of knee brace types. Braces are rarely categorised by design, material or appearance, highlighting the growing need for a unified global framework that considers injury prevention or recovery and design features. Highlighting these issues is important so that future research can address proper terminology for categorising knee braces, to develop a universally agreed categorisation system.

4 Question 3: what are the design components of knee braces?

Knee braces utilise both flexible and stiff Materials like textiles, gels, plastics and metals, and some include hinges for supporting, controlling and guiding knee movements. The design of knee braces generally corresponds to the classification in question 2 and often share common design features (Fig. 2). These include a frame, generally made from lightweight and stiff materials for structural support and padding to enhance comfort around the bony areas of the knee. Straps help to secure the brace to the leg, often accompanied by fasteners, and hinges that allow for controlled movement. These design features will be engineered to meet a specific injury type. For instance, patellofemoral braces feature targeted padding to protect the knee and reduce pain. Single-axis hinges found in prophylactic braces, bend in one simple motion but offer limited protection against excessive rotation of the knee that can harm ligaments and soft tissues. In such braces, hinge misalignment can cause brace slippage, pain and sores [23]. Polycentric hinges [24] in functional braces are intended to better mimic the complex way a knee moves, following its natural trajectory from flexion (bending) to extension (straightening) to limit unnatural twisting of the joint. Whilst the design components of knee braces—such as structure, materials, and joint mechanics—provide a basis for innovation, their development remains complex due to the need to balance stability, mobility and wearer-specific requirements.

As wearable technology advances, research is exploring the inclusion of sensors to measure indices of movement patterns, muscle activity and pressure distribution. Studies have used sensors to monitor brace wearing adherence [21], knee range of motion [25] and rehabilitation [26, 27]. Future work could develop instrumented braces that not only enable real-time measurement, but also offer dynamic support tailored to the user's movement and loading patterns.

5 Question 4: how do we test knee braces?

Testing knee braces is essential to ensure they provide effective support, improve joint stability and reduce the risk of injury or further damage. Testing knee braces involves various approaches to assess usability (to support the knee), mechanics

Fig. 2 Photo showing an example of a functional knee brace on a mannequin, highlighting typical design components. (Author's own image)

(movement with the knee) and user experience (wearability). Testing with users of knee braces provides perspectives into how they influence movement and stability. This approach uses in vivo methods, applying a range of tools commonly used in gait laboratories. For example, wearable sensors or motion tracking systems have been used to quantify changes in joint and gait kinematics related to brace use [28, 29, 30, 31]. In addition, electromyography (EMG) has been used to quantify response of muscle activation patterns to brace wear [32, 33]. However, variables like testing days, test environments, sample characteristics and brace type (given they all differ) can influence study outcomes [34].

Movements, such as pivoting, cutting or landing in sports, can apply external loading to the knee joint, in the inward (varus) or outward (valgus) direction [35]. These external loads can be reduced by a brace that stabilises the knee and resists unwanted movement. One aspect to study is the stiffness of a brace to counteract these loads [36]. Braces made of flexible materials, such as sleeves, tend to be less stiff than prophylactic, functional or unloader, which typically include stiffer materials. These stiffer braces provide more support and stability, but their bulkiness can limit movement [37]. Defining levels of knee brace stiffness is hindered by the lack of a standard for testing them.

In vitro tests, using leg surrogates within mechanical testing rigs, can evaluate brace stiffness under different loading conditions, in multiple directions, such as flexion–extension, medial–lateral and axial rotation38, 39. Such tests have the potential to mimic sporting movements, which can help inform brace design. However, testing conditions and metrics chosen in many studies lack clear justification (e.g. flexion/extension but not axial rotation, loading forces or knee angles), making it difficult to compare findings or apply them to real-world sporting scenarios.

There is currently no universally accepted standard for testing knee braces. Whilst general biomechanical testing guidelines (e.g. plug-ins for gait analysis) and brace classifications outlined in question 2 provide a foundation, the lack of dedicated protocols highlights the need for consistent, validated testing framework. A dedicated standard for knee brace testing could define aspects such as: 1) biomechanical loading (flexion, axial rotation), 2) performance metrics (stiffness, surface friction, slippage and angular restriction) and 3) testing environment (test rigs, gait labs). Future research should clearly explain the choice of testing protocols and metrics to ensure greater relevance, consistency and applicability.

6 Question 5: is there evidence that knee braces impact performance and support recovery?

Optimal health and performance are paramount for any athlete. Athletic performance is defined as the ability to respond effectively to the specific physical demands of the sport [40]. In elite sports, maintaining good health and avoiding injuries are essential for optimal performance. Although a knee injury can compromise an athlete's performance, knee braces can be used for support, stability and recovery. Athletes often resist wearing knee braces, due to concerns about how it may negatively impact their performance, and the social stigma of wearing one [41, 42].

Research suggests that functional and rehabilitation braces support recovery, showing benefits in improving joint stability, reducing pain and aiding in early mobilisation, factors that help return-to-play and reduce the risk of re-injury [10, 43]. However, the impact of wearing a brace on performance remains inconclusive. Some studies imply that prolonged wear of functional braces may slightly improve jump height, speed and agility [44, 45]. Similarly, prophylactic braces—whilst effective in enhancing joint stability—tend to have minimal impact on biomechanical performance, including sprinting, agility and rotational movements [46, 47, 48]. Notably, most existing studies are conducted on healthy individuals, making it difficult to draw direct comparisons with people who have knee deficiencies. In addition, few studies address how factors such as the brace's weight, design features (hinge friction), fit (slippage) and strap tightness may pose risks to an athlete's performance [49, 50]. These factors can affect an athlete's natural movements, due to restrictions placed on the knee joint. Another concern is knee brace effectiveness under high loading conditions, such as in high intensity sports like football, basketball, skiing and rugby [51, 52, 53].

The above factors point to the need for a universal approach to testing knee braces, as outlined in question 4. It is important to establish various factors like type of brace, the injury severity and the demands of the activity. Quantitative methods can assess joint range of motion, gait and movement patterns, with or without a brace, and the brace's design, particularly its mechanical properties. This approach should analyse how the user, brace type and mechanics, and injury are related.

7 Question 6: how can we assess the comfort and user perceptions of knee braces?

Comfort and user experience are often overlooked in knee brace studies. A combined methodological approach is recommended, using both subjective and objective methods. For instance, subjective methods, such as questionnaires and interviews, can be used to analyse how people feel whilst wearing knee braces. Feedback on pain perception, stability and overall satisfaction can be captured directly by asking knee brace users. Objective methods, including movement observation during physical activity and mechanical testing, provide measurable data on brace performance and comfort. When combined, these methods can offer a more comprehensive understanding of the user experience.

Athletes frequently report that comfort and fit can affect their willingness to wear knee braces, because they may hinder performance, confidence, and they also influence consistency of use in managing injuries [54]. Other commonly cited reasons for not using knee braces include skin irritation, poor fit, awkward and bulky designs, limited adjustments and an unfavourable cost–benefit ratio [55, 56, 57]. Since materials are integral to knee brace design, factors that can be measured via thermophysical testing include thermal resistance, breathability and moisture-wicking properties [58]. Insights from sports clothing research—which prioritises comfort, fit and material selection—can inform knee brace testing and design, particularly in addressing user feedback and physical responses to prolonged wear [59]. For example, how people react to clothing, physically (temperature, moisture) and psychologically (comfort, fit) [60, 61].

Observing individuals wearing, adjusting and tolerating braces during physical activity is important for future research. Situating the user within the study ensures they are central to the design and development process [62]. In addition, testing the differences between brace types, the characterisation of various materials and their components, could help us better understand how people use knee braces during activities. This would give a more complete framework for knee brace testing.

8 Question 7: what are the challenges associated with knee braces?

Heavyweight, bulky design, difficulty using, and undesirable appearance are typical issues reported by knee brace users63, 64. Poorly designed braces can fail to provide adequate support or stability, rendering them ineffective. For instance, brace materials may degrade or lose elasticity leading to discomfort or slippage. In addition, the use of synthetic materials, such as polyester and nylon, can limit breathability. Indeed, prolonged wearing of a knee brace can lead to skin irritation, rashes or pressure sores, if it is too tight or lacks breathability [65]. Whilst stiff braces offer more stability, they can be uncomfortable and restrict mobility, making them less practical for sports use. Using less stiff and more skin-friendly materials could address such concerns, leading to better knee brace wearing adherence.

Another issue is the improper size and fitting of knee braces, which often fail to accommodate individual anatomical differences. When braces are incorrectly fitted, they can either be too tight, causing discomfort, or too loose, allowing them to slip [66]. In sport, a poorly fitted knee brace can affect an athlete's performance by moving out of place. This can interfere with movement patterns, potentially increasing fatigue and limiting the range of motion. It remains unclear how knee braces are sized or whether any standard sizing system is followed.

Even when knee braces are properly designed and fitted, their effectiveness relies on adherence to usage. Non-adherence is a widespread issue, with many people failing to wear their braces consistently or use them correctly [67]. Factors contributing to poor adherence include pain, discomfort, inconvenience, complex fitting instructions or misunderstanding of the brace's purpose [68, 69]. There is limited discussion on how brace designs differ across studies. No consensus or comparative studies exist to determine which designs or features are most effective. It is essential to raise clinician and public awareness about the differences between brace types, along with clear guidelines on their appropriate use. In addition, the use of standard sizing systems and simpler more intuitive designs and fitting instructions may improve brace usage. Challenges identified in this question should guide future research towards better knee brace design.

9 Question 8: are there current legislation or regulatory bodies that influence knee brace design or safety standards?

UK athletes are less likely than those in the USA and Australia to use knee braces as a routine preventative measure [47]. Certain sports have strict rules about what can be worn, especially if they have components which may pose a risk to the wearer or other players. Sporting governing bodies such as World Rugby, FIFA and other international sports organisations play an important role in shaping the design and regulation of sports equipment. World Rugby

[70], for instance, state that any equipment must not pose a risk to the wearer or other players. Similarly, FIFA's Laws of the Game [71] instruct that all equipment, including medical supports, must be inspected by officials to ensure they are not dangerous, with emphasis placed on player safety and fairness.

Medical Device Regulations (MDR) 2002 [72] classify knee braces as Class 1, low-risk medical devices. These will include safety and quality markings needed to sell products in the UK and Europe [73]. MDR 2002 [74] also state that all medical devices must comply with essential requirements, as illustrated in Fig. 3. This means that manufacturers of knee braces or healthcare providers, who supply and distribute devices, must adhere to these regulations. Knee braces are not classed as sports equipment, rather as medical devices under the Medical Device Regulation. To see more use of knee braces for pre- or post-injury in sport settings, will require manufacturers to offer designs which better align with both medical device regulations and specific sporting regulatory body requirements. Moving forward, these devices may form part of an athlete's injury management plan.

National and international safety standards also influence knee brace design. The International Standard Organisation (ISO) provides technical specifications for medical devices. For instance, ISO 13485 outlines requirements for quality management systems in medical devices [75]. Compliance with this ensures there is consistency in production, durability and biomechanical effectiveness, ultimately improving patient safety and device reliability. Other standards which could also be used to determine if the brace is fit for purpose, include ISO 13934-1:2013 [76] tensile strength, ISO 12947-2 [77] longevity, BS ISO 10993-1 biocompatibility of materials *that encounter the skin* [78], AATCC 195:2009 [79] for moisture wicking and ISO–11092 for breathability [80]. Despite concerns raised about the quality of material, discomfort and brace adherence, there is no specific legislation solely for knee braces. This means that manufacturers must ensure compliance with the above regulations to guarantee safety and effectiveness of knee braces.

10 Question 9: could redesigning knee braces bridge gaps in health equality?

Sporting bodies like UK Sport, and professional associations like the Institute of Mechanical Engineers (IMechE) are taking an active role in promoting equality [81]. The main goal of UK Sport is to build a world-class sporting system in the UK that is fair, inclusive and ethical, and is athlete-centred and people-focussed [82]. Tokyo 2021 saw the first gender equal Olympic Games, with females comprising 49% of participants and the same number of medals available [83]. Yet, there remains a difference in injury prevention support. Technological advancements are still primarily focussed on male users. Redesigning knee braces has the potential to reduce this gap by making them more accessible and effective for diverse populations.

The World Economic Forum and McKinsey Health Institute [84] report that women's health issues are systematically underfunded and under-researched, leading

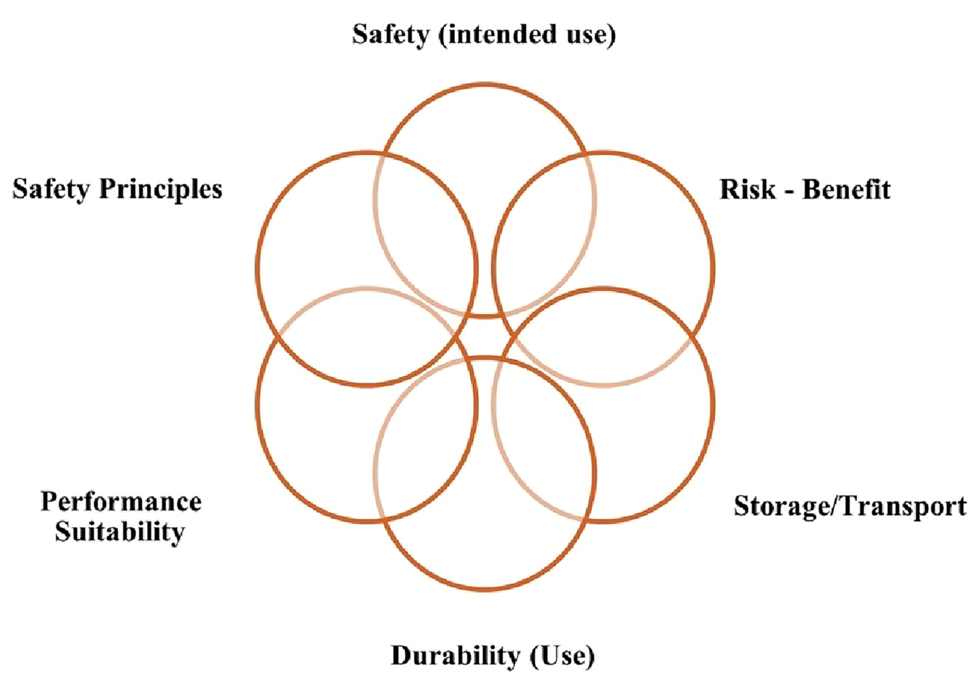

Fig. 3 Figure produced using text from the essential requirements for knee braces, Part II of the UK MDR 2002, Annex I [72]

to health disparities. Despite the higher incidence rate of knee injuries amongst females [85], current knee braces fail to address anatomical and biomechanical differences amongst demographics. For example, whilst osteoarthritis is more common in women than men, the latter are more likely to continue wearing knee braces [86]. This is largely because poorly fitting knee braces can lead to discomfort over extended periods, particularly for females [87, 88]. Females generally have wider hips and different knee alignments than men, which can affect how a knee brace fits and functions. This means that manufacturers of knee braces should consider integrating more adjustable sizing and customisable components to accommodate anatomical and biomechanical differences between sexes to ensure proper fit and conformability.

Integration of advanced technologies into knee braces could further bridge the gap. The concept of the 'digital athlete' can help improve monitoring and recovery of players [89]. Development of "intelligent" wearable knee braces equipped with assistive technology can offer continuous monitoring during rehabilitation [90]. In addition, simplifying brace design with lightweight materials, whilst still maintaining adequate support, could enhance comfort and allow for greater freedom of movement. Contoured padding and adjustable straps could be used to accommodate a wider range of body shapes and improve comfort without sacrificing stability or support. Redesigning knee braces has the potential to bridge gaps in health equality, but only if affordability and accessibility are prioritised. That said, the cost of a new technology tends to decline over time, especially with increased production and adoption.

11 Question 10: what are the future opportunities and research directions for knee brace design and functionality?

Whilst tracking and health monitoring devices are commonly seen on athletes, wearable devices providing a more holistic health monitoring approach may be seen in the future [91]. Use of artificial intelligence and digital technology is still relatively new, requiring further developments and careful analysis. Yet, there are clear benefits for their use in sports. Combining both has the potential to identify those at risk before (re)injury occurs. This could potentially revolutionise the way athletes prepare, avoid, respond and recover from an injury [92]. Knee brace research is now focussing on personalised designs [93] and smart technologies [94], supported by rigorous testing protocols.

Sensors and actuators in knee braces are offering ways to track knee movements and respond quickly to overloading signs [17]. These signs include sudden inward–outward twisting of the knee joint, or excessive joint compression, which can cause injury [95]. For example, an artificial intelligence-programmed knee brace, using sensors, has been developed which can actuate an airbag to tighten around the knee joint when it is compromised [96]. Similarly, incorporating sensors into knee braces allows for the measurement of knee joint angles throughout movement in a structured and repeatable manner. These features can control loading and prevent excessive twisting in the knee, aiding, rather than hindering, its natural movement [97].

Future opportunities May also look to incorporate biomechanical differences and Sport-specific demands in knee braces. For instance, 3D-printed custom-fitted knee braces may improve functional use, by improving comfort, conformability and fit [98]. Standard testing to evaluate mechanical properties, load distribution and long-term degradation and wear through real-life sports scenarios is needed. Embedding artificial intelligence programmable knee braces could provide real-time data, for continuous monitoring of athletes during rehabilitation. These could transform knee braces from being just support devices, into responsive devices capable of injury prevention [99]. To drive innovative knee brace design, especially through wearable technology or artificial intelligence-driven solutions, more data are needed, particularly regarding the mechanics of knee injuries and associated risk factors. Current reliance on assumptions and limited evidence makes it difficult to evaluate the effectiveness of knee braces in support, injury prevention and rehabilitation.

12 Discussion

Injuries are an inevitable part of sport, often affecting performance and career longevity [11]. Yet, many still overlook the role of knee braces—particularly during rehabilitation [100]. Most research has focussed on testing one type of knee brace for specific injuries, offering limited insight into wearer behaviour and attitudes toward bracing. Research is also focussing on integrating wearable technology to track movement and health of athletes. However, more data are needed to effectively advance these technologies in sport. In addition, little to no research has explored how anatomical differences—such as those between males and females—should inform knee brace design. Whilst the higher incidence of ligament injuries in female athletes is well documented, this knowledge has yet to be effectively applied within sports technology and product development.

The effectiveness of knee bracing remains unclear, and applying research in real-world sports settings continues to be a challenge. This disconnect is influenced by factors such as athlete attitudes, logistical constraints in sporting environments, and a lack of clear understanding around brace function and application. This ten questions paper highlights the growing need to evaluate the effectiveness and use of knee braces more systematically and holistically. A key challenge lies in the inconsistent and often unclear categorisation of knee braces. In addition, the lack of standardised testing limits the understanding of brace performance in real-world settings. To help address these issues, a universal classification system and clearer terminology is required. A systems approach to using knee braces to address sports-related injury is needed. This would involve considering the knee brace not as a standalone product, but as part of an interconnected framework in which the design, user needs, injury type, biomechanics, performance demands and even psychological factors are all considered.

13 Conclusion

As more people engage in sports to support a healthy and active lifestyle, the demand for knee braces continues to grow. Whilst current research has laid important groundwork, there is now a clear need for a more holistic approach to knee brace testing. There is also a growing need to design braces specifically for females. We aimed to provide new insights into the field and identify directions for advancing knee brace research. In summary, establishing unified guidelines for appropriate use and integrating standardised mechanical testing with user experience would provide a more holistic and practical approach to knee brace evaluation.

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