

RESEARCH ARTICLE

Biomechanics

Ergonomic assessment and gait analysis of a knee joint model with an active spring-reinforced centrally-rollable knee bypass support system

P Ponram^{1*}, C Mythili¹, NC Selvakumar² and A Selwyn J Kumar³

¹ Department of Electrical and Electronics Engineering, University College of Engineering Nagercoil, Konam, Kanyakumari District, Tamil Nadu, India.

² Government Primary Health Centre, Thadikaara Konam, Kanyakumari District, Tamil Nadu, India.

³ Kanyakumari Government Medical College, Asaripallam, Kanyakumari District, Tamil Nadu, India.

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Abstract: Musculoskeletal issues can lead to severe immobility problems when not identified and addressed early. An ergonomic assessment and gait analysis of a novel knee joint model featuring an innovative active spring-reinforced centrally-rollable knee bypass support system was conducted in this work. The study employed computer simulations using human knee joint models integrated with the proposed knee support system. Gait parameters, joint angles, and muscle activations were assessed to evaluate the system's effects on knee joint stability, impact forces, and gait mechanics during various activities. The knee support system notably improved knee joint alignment, lessened joint forces, and optimized muscle activation patterns. The knee bypass support system facilitated a natural knee roll during walking and running, ultimately enhancing gait efficiency and reducing joint stress. The study's findings showcase improved biomechanics, which hold promising implications for injury prevention, rehabilitation, and overall performance enhancement. With the support system, dynamic changes in tendon forces during activity enhanced the knee joint stability and coordination, which will improve performance and injury prevention. Balance of forces during different activities also encompassed the joint stability. The knee support system demonstrates its potential to address musculoskeletal issues by enhancing knee joint stability and optimizing gait mechanics. This innovation could significantly contribute to minimizing immobility concerns and improving individuals' quality of life.

Keywords: Biomechanics, ergonomic assessment, gait analysis, knee joint model, knee support system.

INTRODUCTION

Musculoskeletal knee issues are a common problem that affects people of all ages, from athletes to the elderly. The knee joint is made up of bones, ligaments, tendons, and cartilage, and is vulnerable to a variety of injuries and conditions. Some of the most common causes of knee pain include overuse injuries, such as tendinitis and bursitis, as well as ligament and cartilage injuries, such as anterior cruciate ligament (ACL) tears and meniscus tears. Osteoarthritis, a degenerative joint disease, is another common cause of knee pain, especially in older adults. Other contributing factors to knee pain include obesity, genetic predisposition, and certain medical conditions, such as rheumatoid arthritis. Proper diagnosis and treatment of knee issues are important in preventing further damage and improving overall quality of life (Barr, 2007).

Musculoskeletal knee issues are often linked to lifestyle factors such as physical activity, diet, and weight management. Individuals who engage in high-impact sports or repetitive motions, such as running or jumping, may be at increased risk for knee injuries such as sprains, strains, or tears (Hunt, 2003). Being overweight or obese can also put added stress on the knee joint, increasing the risk of developing conditions such as osteoarthritis.

* Corresponding author (ponraam@gmail.com;  <https://orcid.org/0000-0002-5489-3436>)



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On the other hand, a healthy diet and regular exercise can help improve joint health and reduce the risk of knee issues (Messier *et al.*, 2006). Adopting a healthy lifestyle can play an important role in preventing and managing musculoskeletal knee issues (Bliddal *et al.*, 2014).

Musculoskeletal issues can be a significant source of discomfort and can limit one's ability to perform everyday activities. Knee support braces can be a helpful aid in managing knee pain by providing additional support and stability to the knee joint (Valachi & Valachi, 2003). These braces are designed to fit securely around the knee and can help reduce pressure on the joint, providing relief from pain and discomfort. While knee braces are not a cure for musculoskeletal issues, they can be a useful tool in managing symptoms and improving quality of life (Quinlivan *et al.*, 2015).

Active knee support braces are currently explored to offer dynamic knee load support and distribution (Alluhydan *et al.*, 2023). Spring based braces provide dynamic changes to muscle forces ensuring optimal function and comfort (Dereshgi *et al.*, 2023).

Current trends in musculoskeletal knee brace support involve the use of advanced materials and design features to provide maximum comfort and effectiveness. One trend is the use of neoprene and other lightweight materials that offer a snug, yet breathable fit, reducing discomfort and irritation (Zhao *et al.*, 2022). Another trend is the use of adjustable straps and hinges that allow for a customized fit and targeted support to specific areas of the knee (Ultich *et al.*, 2007). Additionally, many knee braces now incorporate compression technology, which provides targeted compression to reduce swelling and promote healing. In terms of design, some knee braces feature an open patella design, which helps to relieve pressure on the knee cap and reduce pain. Others feature a closed patella design, which provides additional support and stabilization to the knee joint. Finally, many knee braces now incorporate smart technology, such as sensors or tracking software, to monitor the user's activity levels and provide real-time feedback on performance and progress (Kraemer *et al.*, 2004). Overall, the latest trends in musculoskeletal knee brace support reflect a focus on comfort, customization, and advanced technology to provide effective support and management of knee issues.

A number of studies were made in the area of prevention of knee injuries. Study of treatment therapies, support systems and life style change to prevent knee musculoskeletal disorders are widely reported.

In recent research, Hunte *et al.* (2020) introduced an assist-as-needed control strategy for a soft knee assistive device, utilizing a custom-built device and a muscle synergy-based walking model. Saccares *et al.* (2017) proposed an innovative method for estimating knee joint torques for assistive devices with reduced sensor requirements, enabling a wearable setup. Zhang *et al.* (2019) discussed advancements in knee assistive devices, covering mechanical design, sensing, control systems, and performance evaluation. Kim *et al.* (2020) developed a joint apparatus with flexures supporting a bar extension, while Osinga *et al.* (2020) designed an apparatus for degenerative joint conditions with elastic buffering mechanisms. Yang *et al.* outlined a challenging treatment concept for knee periprosthetic joint infection and extensor apparatus deficiency. Comer *et al.* devised a joint sensor assembly for screed applications, controlled by a valve signal. Zhao *et al.* described effective management of multiple knee ligament injuries and extensor apparatus rupture. Malone *et al.* patented rehabilitation apparatus for knee flexibility post-surgery, and Wang *et al.* introduced a wearable exoskeleton seat with thigh, knee, and shank mechanisms. Finally, Hsu *et al.* patented a knee massage apparatus with an L-shape structure and integrated massage devices, controlled by a CPU and PCB.

Cernohorsky *et al.* (2018) focused on developing a special knee brace for intensive rehabilitation that can also be used daily. They utilized modern drive control systems and status information from drives for sensor-less diagnostics. The brace's design integrated 3D scanning and printing for construction, while the mechatronic system emphasized energy efficiency and lightweight design. Reanaree *et al.* (2018) aimed to assist patients with paralysis through an exoskeleton suit supporting body movement for improved functioning, incorporating a microcontroller-driven system and movement mechanism. Auberger *et al.* (2018) introduced an orthotic system for lower limb paralysis support, featuring a computer-controlled knee joint unit with sensors, hydraulics, and a lever mechanism for controlled motion. Hafizah Amer *et al.* (2020) explored a novel knee support design using a controllable damper unit with magneto-rheological technology to absorb impact, considering its damping characteristics and magnetic damper's behaviour.

Johnson *et al.* (2023) validated the clinical application of a spring loaded knee support system for dynamic unloading during gait. The proof of concept was based on fluidic actuator elements devoid of electronic controls.

Despite advances in musculoskeletal knee brace support technology, there are still some research gaps that need to be addressed. One area that requires further investigation is the long-term effectiveness of knee braces in preventing or managing knee pain and injury. While some studies have shown positive results, more research is needed to determine whether knee braces can provide sustained benefits over time. Additionally, there is a need for further research on the optimal design and fit of knee braces, as not all knee braces may be equally effective for all individuals or types of knee issues. Another area for further investigation is the potential side effects of knee brace use, particularly over extended periods of time. While knee braces are generally considered safe, there is a need for more research on potential risks, such as skin irritation or reduced muscle strength due to prolonged use. Finally, there is a need for more research on the cost-effectiveness of knee braces, as they can be expensive and may not be covered by insurance in all cases. Overall, further research is needed to better understand the effectiveness, safety, and cost-benefit of musculoskeletal knee brace support systems.

MATERIALS AND METHODS

The objective of the project is to design a knee bypassing apparatus used for elderly and obese persons for knee load distribution. The proposed project intended to prevent knee joint disorders such as overlap and joint pains for aged and obese peoples. Knee joint disorders are prevalent in aged persons due to wear of knee joints and overlap due to aging. This will cause mobility disorders and knee joint problems such as severe pain. By reducing the net load over knee joints, by an external load bypassing apparatus across knee joints, the overlap of joints will be reduced. This will ultimately prevent elders from undergoing knee replacement surgeries and getting immobility disorders.

Other than preventive care, this apparatus will also be a supportive mechanism for knees of aged persons who have knee joint issues. The design must be validated for ergonomic compatibility of the design with computer simulations. Validation and analysis of load distribution efficiency through computer simulation needs to be done.

The components of the knee joint apparatus such as the circular roller and side beads are the innovative components of the work. The circular roller part is able to hold the upper and lower load bearing side beads, and

simultaneously provides for knee movement. Further it will be able to pass the load from the upper side to the lower side through a bypass arrangement. The entire system in terms of design and way of work is novel and innovative.

Rapid tools like 3D printing enable rapid prototyping and customization of knee support braces, allowing for quick iterations and adjustments based on user feedback. 3D scanning facilitates precise measurement and modelling of individual anatomies, ensuring optimal fit and comfort of the brace. These technologies streamline the design and development process, reducing time-to-market and costs associated with traditional manufacturing methods. Additionally, they offer the flexibility to incorporate complex geometries and materials for enhanced performance and support. Overall, leveraging 3D printing and scanning accelerates innovation and improves the effectiveness of knee support brace solutions.

Knee joints models were created by three dimensional scanning of knees of different age groups with EinScan Pro 2X scanner having scanning accuracy of 0.045 mm and scanning speed 10 fps, 3,000,000 points/s. The models were processed with i7 Intel Processor and NVIDIA GTX 1080 Graphic processor with 4GB RAM.

The portable 3D scanning enables creation of models of knee joint anatomy and also provides for universalisation of sizes. This incorporates a number different size and shaped knee joint models to be evaluated in this study.

The models were fitted with a custom designed knee-bypass support system having a spring-reinforced and centrally rollable mechanism. The spring reinforcement enables effective load transfer between upper and lower thighs bypassing the knee joint. The central roll mechanism enables hassle free movement of the knee while fitting the support system. Support frames were drawn from the upper thigh region laterally to accumulate at the centre of the knee joint point, which was further drawn back to the lower thigh laterally from the converging central point.

The central converging points for upper and lower thighs are interconnected by rollable and spring reinforced mechanism, the support system is fitted to the knee joint models also by effecting various upper and mobility load points to stimulate the load analysis over the knee and support system.

Musculoskeletal geometry refers to the study of the structure and arrangement of muscles and bones in the human body. In the current model, the musculoskeletal geometry of knee joint bone and muscles was evaluated for the working of forces of muscle and bone. The movement of knee area is simulated in 400 frames for a body mass index of 86. The normal forces of muscle and joints were pre loaded. The movement of the knee joint for a standard jump is simulated. The muscle and joint forces were calculated. The level of activity of muscle elements is represented in colour, in which red represents more activity.

Forces in hip musculature, knee musculature, ankle musculature, joint contact forces, and peak joint contract forces were simulated in this work.

The activities simulated were bottom of the counter movement, middle of propulsive phase, and take off. The analysis encompasses the physical and mathematical analysis of the geometry of joints, muscles, and bones to better understand their function and movement. This analysis is a crucial one in developing models of human movement, design of knee support braces, and designing prosthetics and orthotics. It is crucial to ensure that these designs are anatomically correct, ergonomically useful and that the materials used mimic the natural musculoskeletal system to ensure maximum functionality. A thorough understanding of knee musculoskeletal geometry is necessary for effective rehabilitation, injury prevention, and overall physical health.

The position of muscle and bone segments, position of patella and patellar tendon, centres of joints, rotation, and tibio-femoral joint contact points were measured during resting and activity.

The knee joint is a complex joint that allows for movement in multiple planes. Kinematics, the study of motion without consideration of forces, is an important aspect of understanding the knee joint's function. The knee joint is composed of two main bones, the femur and the tibia, which articulate with each other. The patella, or kneecap, is also part of the joint and helps to stabilize it.

During flexion and extension of the knee joint, the femur rolls and glides on the tibia. This movement is necessary for the knee joint to bend and straighten. The amount of motion that occurs during flexion and extension depends on the individual and can be influenced by factors such as muscle strength, ligamentous laxity, and previous injuries.

The knee joint also has some degree of rotational motion, which occurs during activities such as pivoting or twisting. This rotation is facilitated by the shape of the femoral condyles, which allow for slight internal and external rotation of the tibia.

In addition to the rolling and gliding motion of the femur on the tibia, there is also some degree of translation that occurs during knee joint motion. This translation refers to the anterior and posterior movement of the tibia relative to the femur. During knee extension, the tibia moves anteriorly, and during knee flexion, the tibia moves posteriorly.

The kinematics of the knee joint are complex and multifaceted. Understanding the various types of motion that occur at the knee joint is essential for diagnosing and treating knee injuries and conditions.

The dynamics of the knee joint refer to the study of the forces that act on the joint during movement. These forces are generated by the muscles, ligaments, and bones that make up the knee joint.

During activities such as walking, running, and jumping, the knee joint is subjected to high forces. These forces are distributed across the joint and are necessary for generating movement. However, if the forces are not distributed evenly or if they exceed the joint's capacity, injuries can occur.

The knee joint is stabilized by a variety of structures, including the ligaments, menisci, and muscles. These structures work together to maintain the joint's stability and prevent excessive motion or displacement.

The quadriceps and hamstrings muscles are particularly important in the dynamics of the knee joint. The quadriceps are responsible for extending the knee, while the hamstrings are responsible for flexing the knee. These muscles work together to control the forces that act on the knee joint and ensure that the joint moves in a controlled and safe manner.

Mathematical model of the knee joint dynamics

The following mathematical models provide a comprehensive framework for designing a knee joint support apparatus. The Knee Joint Stability Model formulates an equation that accounts for various forces acting on the knee joint, including those from muscles, ligaments, gravity, and the support system itself, to

ensure equilibrium. Incorporating equations for specific muscles and ligaments based on their activation levels and mechanical properties enhances the model's accuracy. The Gait Mechanics Model describes the relationship between knee and hip joint angles during walking or running, considering muscle activations and biomechanical principles. The Knee Roll Mechanism Model delineates the dynamics of the knee roll mechanism, crucial for understanding how the support system interacts with knee movement. The Impact Reduction Model quantifies the support system's effectiveness in reducing impact on the knee joint during activities, providing a measurable outcome for performance evaluation. Finally, the Optimal Spring Stiffness Model aims to identify the optimal stiffness for the support system by minimizing an objective function considering factors like joint stability, energy efficiency, and user comfort. By considering both muscle and ligament dynamics, these models provide a holistic approach to designing a knee support apparatus that ensures stability, functionality, and user satisfaction. Additionally, understanding the roles of specific ligaments further informs the design process, emphasizing the importance of comprehensive biomechanical considerations in developing effective knee support solutions.

Knee joint stability model

Let F_{muscles} represent the forces exerted by muscles around the knee joint, $F_{\text{ligaments}}$ be the forces from the ligaments, F_{gravity} is the gravitational force, F_{support} represents the force from the active spring-reinforced knee bypass support system, and F_{reaction} is the joint reaction force.

The equation for knee joint stability can be formulated as:

$$F_{\text{reaction}} = F_{\text{muscles}} + F_{\text{ligaments}} + F_{\text{gravity}} + F_{\text{support}}$$

This equation represents the equilibrium of forces acting on the knee joint. The model should also include the equations that describe the forces from specific muscles and ligaments based on their activation levels and mechanical properties.

Gait mechanics model

The gait mechanics model can include the equations for joint angles and muscle activations during walking or running. Let θ_{knee} represent the knee joint angle, θ_{hip} be the hip joint angle, and A_{muscles} denote the activation levels of muscles around the knee and hip.

The equations for gait mechanics can be expressed as:

$$\theta_{\text{knee}} = f(\theta_{\text{hip}}, A_{\text{muscles}})$$

$$\theta_{\text{hip}} = g(\theta_{\text{knee}}, A_{\text{muscles}})$$

These equations describe the reciprocal relationship between knee and hip joint angles during gait. The model should also include equations for muscle activations based on biomechanical principles and muscle recruitment patterns during different phases of the gait cycle.

Knee roll mechanism model

Let θ_{roll} represent the knee roll angle, k_{spring} be the spring stiffness, b_{damping} denote the damping coefficient, and τ_{torque} be the torque applied by the spring-reinforced knee bypass support system.

The equations for the knee roll mechanism can be defined as:

$$\tau_{\text{torque}} = k_{\text{spring}} * \theta_{\text{roll}} + b_{\text{damping}} * (d\theta_{\text{roll}}/dt)$$

These equations describe the dynamics of the knee roll mechanism, where the torque from the support system is a function of the knee roll angle and its angular velocity.

Impact reduction model

To assess the impact reduction capabilities, let $F_{\text{knee_without_support}}$ and $F_{\text{knee_with_support}}$ represent the forces transmitted through the knee joint during activities without and with the knee support system, respectively.

The equation for impact reduction can be given as:

$$\text{Impact_Reduction} = (F_{\text{knee_without_support}} - F_{\text{knee_with_support}}) / F_{\text{knee_without_support}} * 100$$

This equation calculates the percentage of impact reduction provided by the support system compared to the forces experienced without the support system.

Optimal spring stiffness model

Let k_{optimal} represent the optimal spring stiffness for the knee support system, and J is an objective function that quantifies the effectiveness of the support system. The objective function J can include factors such as joint stability, energy efficiency, and user comfort.

The equation for the optimal spring stiffness can be defined as:

$$k_{\text{optimal}} = \text{argmin } J(k_{\text{spring}})$$

This equation finds the spring stiffness that minimizes the objective function J , indicating the optimal stiffness that achieves the desired level of knee support and overall performance of the support system.

In addition to the muscles, the ligaments of the knee joint also play a crucial role in the joint's dynamics. The medial and lateral collateral ligaments help to prevent excessive side-to-side motion, while the anterior and posterior cruciate ligaments help to control the forward and backward motion of the knee joint.

Overall, the dynamics of the knee joint are complex and involve a variety of structures and forces. Understanding

these dynamics is essential for preventing and treating knee injuries and conditions.

RESULTS AND DISCUSSION

The geometry of knee joint muscle forces during active phase is given in the Figures 1, 2, 3, and 4. The figures provide a multilateral point of view in which various muscle forces are simulated against time during the knee joint action (like jumping or walking). The different muscle forces were colour coded with respect to the intensity of force. Dark red representing the most intense force, it can be seen that the patella and meniscus are exerting maximum force reaction during the activity. The simulation was done with and without brace support and the numerical difference in force at these two muscles (patella and meniscus) in focus were recorded.

Geometry of Knee Joint Muscle Forces during Active Phase

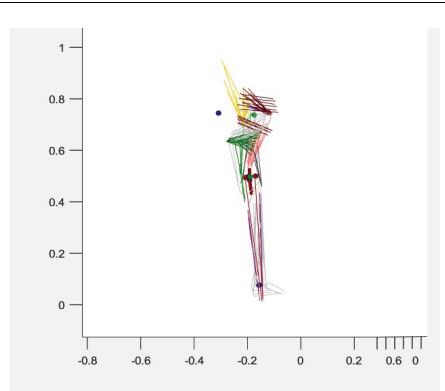


Figure 1: Front view of knee joint forces

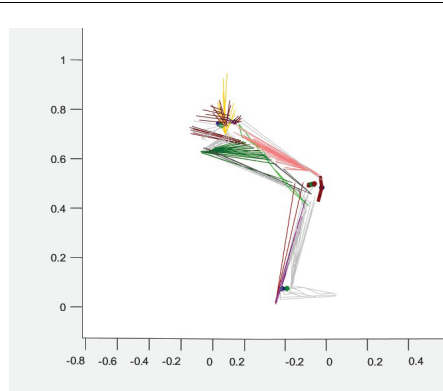


Figure 2: Lateral (Right) of knee joint forces

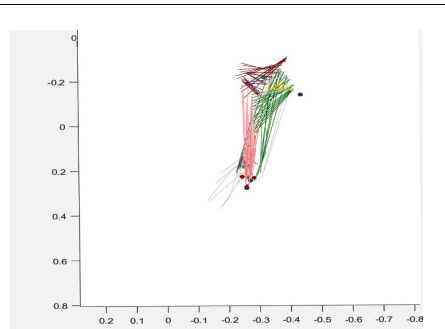


Figure 3: Top view of knee joint forces

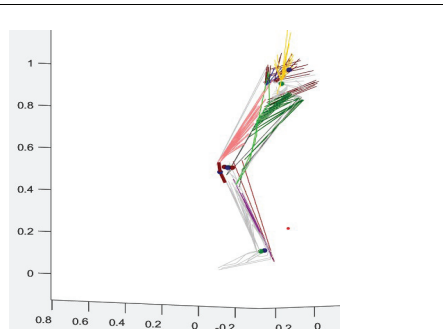


Figure 4: Lateral (Left) of knee joint forces

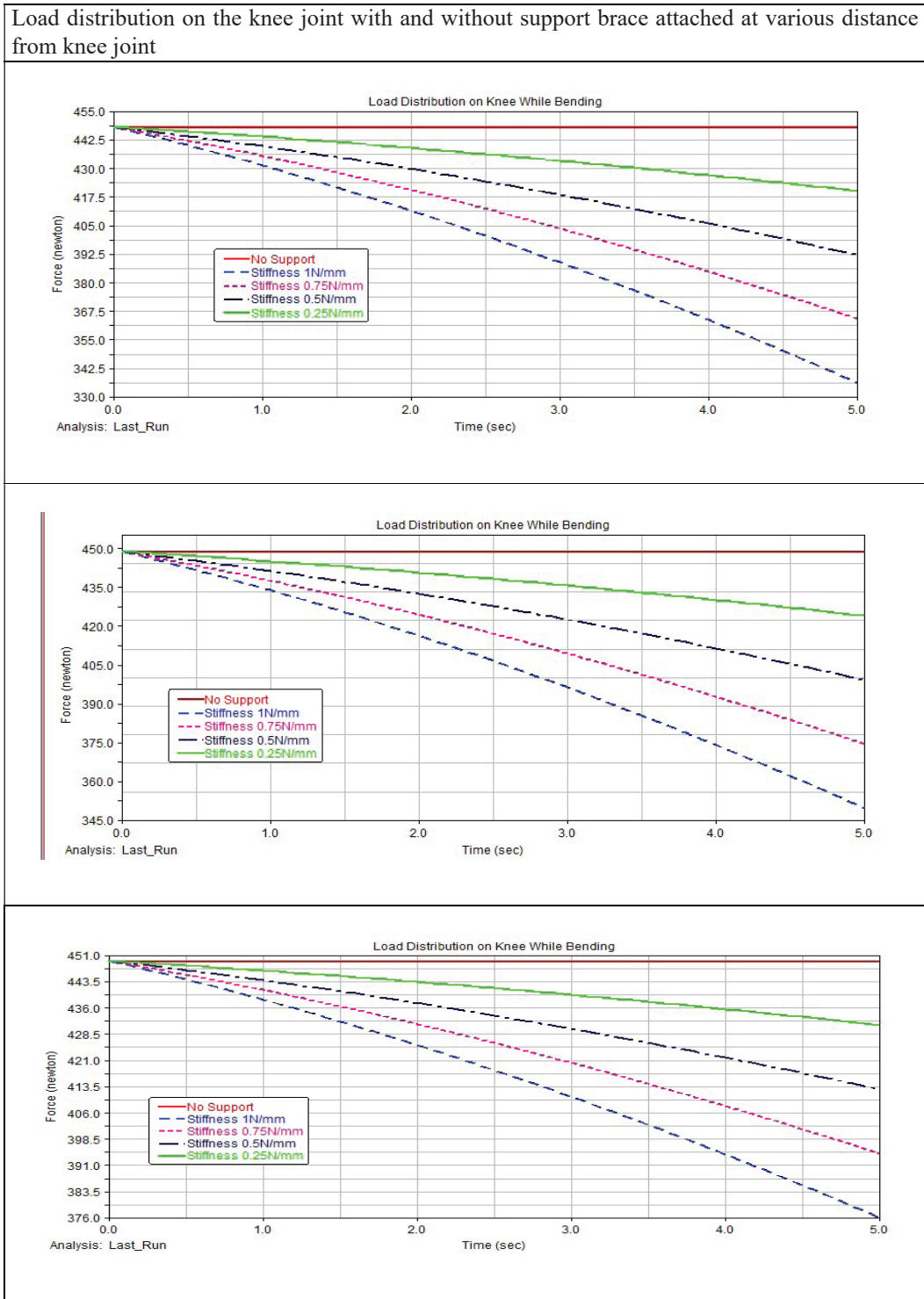


Figure 5: Load distribution on the knee joint with and without braces placed at various distance from knee joint
 (a) Brace placed near to Knee (b) Brace placed at a distance of 50 mm (c) Brace placed at 100 mm

A knee joint model with and without brace support was simulated and the results were given in Figure 5. It can be seen that no load distribution occurs when no support brace was placed. The load was applied over the femur and transferred to the tibia through the knee joint. The stiffness of the spring used in the brace was adjusted as 0.25 N/mm, 0.5 N/mm, 0.75 N/mm and 1 N/mm. It can be interpreted from Figure 5 that irrespective of the placement of the support brace over the knee, the spring with maximum stiffness provides effective load distribution. Also, load distribution was more effective when the braces were placed at farther contact points from the knee than closer to the knee joint. However placement of the brace at a farther point beyond the optimum comfort zone of the user may be ineffective when comes to ergonomic usability and knee mobility when the braces were placed.

The knee-joint was modelled in CREO software and the simulation by application of forces were done using the ADAMS.

Knee joint forces in action during movement

In this section the simulated knee joint forces with respect to knee joint movement is discussed. Figure 6 represents the plot of forces in hip musculature against time during a motion, where ADD represents Adductors and GL represents Gluteus Maximus.

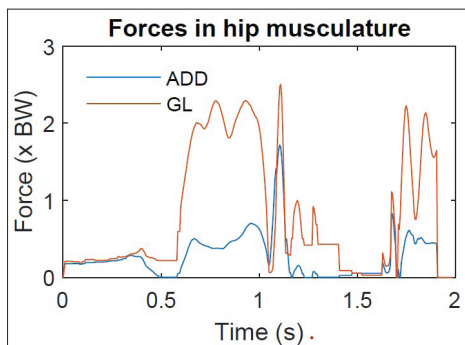


Figure 6: Hip Muscle Forces During

At 0.5 seconds, the Adductors decrease their force to zero, while the Gluteus Maximus maintains its force. This suggests that the Adductors' contribution reduces, possibly as the movement transitions from one phase to another, while the Gluteus Maximus continues to stabilize the hip. At 0.6 seconds, the Adductors start activating again, suggesting their involvement in the movement.

The Gluteus Maximus exhibits a sudden peak in force, indicating a dominant role in generating force during this phase.

The plot describes the forces generated by these muscles relative to time, and different phases and patterns can indicate various muscle actions and contributions. The plot suggests a complex interplay between the Adductors and Gluteus Maximus during the movement. The Adductors seem to play a significant role in generating force at specific moments, while the Gluteus Maximus exhibits both dominant and cyclical force patterns. This pattern of activation and coordination between the muscles is likely tailored to the specific demands of the activity or exercise being performed, such as walking, running, or a specific hip exercise. The plot highlights the dynamic nature of hip muscle function during the movement and showcases their ability to work together to stabilize and produce force throughout different phases

The graph represents the forces exerted by various knee musculature (RF - Rectus Femoris, VAS - Vastus, BIH - Biceps Femoris, and PT - Popliteus) over time during a specific activity or movement.

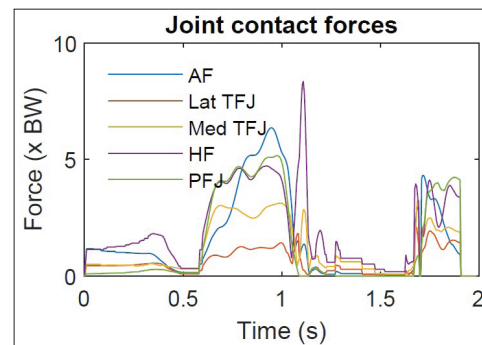


Figure 7: Knee muscle forces during action

The graph illustrates the temporal pattern of muscle activation and relaxation during the specified activity, likely involving knee movements. The initial gradual rise and subsequent sharp increases and decreases in forces suggest specific phases of muscle activation and coordination. Further context and information on the nature of the activity or movement would be required to provide a more detailed and comprehensive interpretation of the results.

The proposed system improves the gait symmetry which implies that the user shall be able to Gair was

appeared to be in symmetry with the knee support brace. The outcome was consistent with similar studies, which validates the gait performance but with different types of knee braces (Li *et al.*, 2023).

The implications of the muscle forces depicted in the graph can provide valuable insights into the functionality and coordination of the knee musculature during the specified activity. Here are some possible implications based on the patterns observed:

1. **Gradual Activation and Coordinated Increase:** The initial gradual rise in muscle forces (RF, VAS, and BIH) indicates a synchronized activation of these muscles at the beginning of the activity. This coordinated increase suggests that these muscles work together to initiate and support the movement, ensuring stability and control during the early phase.
2. **Steady State and Sustained Activation:** The period between 0.4 seconds and 0.5 seconds, during which all the forces maintain a constant level of 0.2 force, indicates a steady state of muscle activation. This sustained activation might be related to maintaining a specific posture or holding a position during the activity.
3. **Sharp Increase in Forces:** The sharp increase in forces at 0.6 seconds, particularly for VAS, BIH, PT, and VAS RESPECTIVELY, suggests a rapid and intense activation of these muscles. This sudden surge in forces could be associated with a more demanding phase of the movement, such as a quick change in direction, jumping, or landing.
4. **Differential Muscle Activity:** The differences in the timing of force reduction and relaxation among the muscles have implications for their roles during the activity. For instance, the delayed reduction of force in BIH compared to other muscles (at 1.2 seconds) indicates that BIH may be involved in providing ongoing support or stability even after other muscles have ceased their activity.
5. **Fluctuating Forces:** The fluctuation of forces between 0 force and 0.3 force between 1.2 seconds and 1.7 seconds suggests a transitional or stabilizing phase of the activity. These fluctuations could be related to fine-tuning movements or accommodating changes in the task's demands.
6. **Specific Roles of RF and PT:** The drop in forces to zero for RF and PT at 2 seconds suggests that these muscles might not be as critical during the later phase of the activity. This could imply that other muscles or mechanisms take over to complete the movement or stabilize the knee joint.

The implications on the muscles suggest a complex and coordinated interplay of different muscle groups during the specified activity. The muscle activation patterns indicate how the knee musculature adapts to varying demands and plays specific roles in supporting movement, stability, and control. Understanding these implications can be crucial in designing targeted rehabilitation programs, optimizing athletic performance, or addressing knee-related issues in elderly and obese populations. However, it is essential to interpret the results in the context of the specific activity and consider other factors that may influence muscle behaviour, such as individual differences and external conditions.

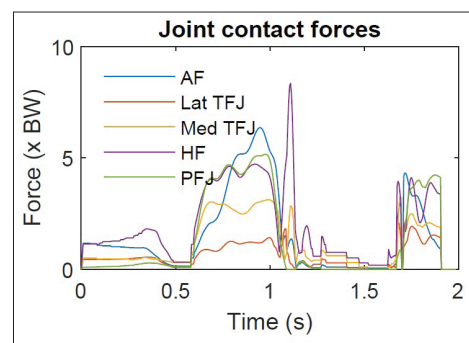


Figure 8: Contact forces at knee joint

The plot demonstrates the dynamic changes in joint contact forces over time during the specific activity or exercise. There are distinct phases of force development and changes in loading patterns across the different joint regions (Medial and Lateral Tibiofemoral Joints, Hip Joint, Patellofemoral Joint, and Ankle Joint). The force values provide valuable insights into the loading and force distribution across the various joints, which can be important for understanding joint mechanics, muscle activation, and potential implications for joint health and performance during the analyzed activity.

The joint contact forces described in the plot provide valuable information about how different joints are loaded and experience forces during a specific activity or exercise. Understanding joint contact forces is essential for assessing the biomechanics of the musculoskeletal system and gaining insights into the stress and load distribution across various joints. Here's what the plot means for joint contacts:

1. **Joint loading patterns:** The plot shows the time-dependent changes in joint contact forces for several

key joints, including the medial tibiofemoral joint (Med TFJ), lateral tibiofemoral joint (Lat TFJ), hip joint (HF), patellofemoral joint (PFJ), and ankle joint (AF). The pattern of force changes over time indicates how these joints experience loading during the activity.

2. Force magnitude: The peak force values reached by each joint during specific phases of the activity indicate the maximum load they bear. For example, the HF reaches a peak force of 9 BW, suggesting that the hip joint is subjected to relatively high forces during certain phases of the activity. On the other hand, the PFJ reaches a peak force of 5 BW, indicating the magnitude of forces experienced by the patellofemoral joint.
3. Phase-specific behaviour: The plot shows distinct phases in force development and behaviour for different joints. For example, there is an initial burst of force generation around 0.5 seconds, followed by a period of relative stability with slightly elevated forces. This may indicate the different phases of movement during the analyzed activity.
4. Force distribution: By comparing the forces at different joints, we can understand the distribution of forces across the lower extremity and its impact on joint mechanics. For instance, the Lat TFJ may experience higher forces than the PFJ and AF during specific phases, indicating the importance of lateral stability during certain movements.
5. Joint health implications: Joint contact forces are crucial for assessing joint health and potential risks of overloading or joint injuries. High peak forces, particularly at the hip and knee joints, may indicate increased stress on these joints, which can be relevant for athletes, individuals with certain activities or exercises, or patients with certain conditions.
6. Biomechanical insights: Analyzing joint contact forces helps researchers and clinicians understand the biomechanics of movement and the interplay between muscles, bones, and joints. This knowledge can inform the development of rehabilitation protocols, injury prevention strategies, and optimized movement patterns.

In summary, the joint contact forces in the plot provide valuable information about how the forces are distributed across various joints during the activity. This information can be crucial for understanding joint mechanics, optimizing movement patterns, assessing joint health, and designing targeted interventions to improve performance and prevent injuries.

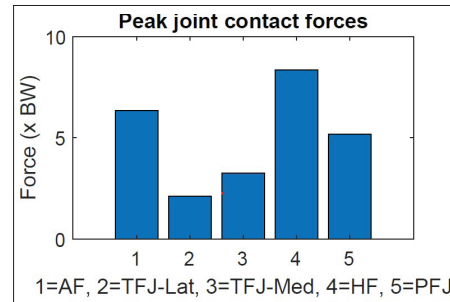


Figure 10: Peak joint contact forces

1. TF (total force) = 6 BW:
The total force (TF) experienced by the joint system is 6 times the body weight. This includes the combined forces acting on all joint regions (lateral tibiofemoral, medial tibiofemoral, hip, and patellofemoral joints). A total force of 6 BW indicates the overall loading on the entire joint system during the specific activity or exercise being studied.
2. TFJ-LAT (total force at lateral tibiofemoral joint) = 2 BW:
The total force at the lateral tibiofemoral joint is 2 times the body weight. This specific force value represents the load experienced at the lateral side of the knee joint during the activity. It indicates the contribution of forces acting on the lateral aspect of the tibiofemoral joint, which is crucial for lateral stability during movements such as cutting or side-stepping.
3. TFJ-MED (total force at medial tibiofemoral joint) = 3 BW:
The total force at the medial tibiofemoral joint is 3 times the body weight. This value represents the load experienced at the medial side of the knee joint. The medial tibiofemoral joint plays a critical role in weight-bearing and shock absorption during activities like walking, running, and jumping.
4. HF (force at hip joint) = 9 BW:
The force at the hip joint is 9 times the body weight. This value indicates the significant loading experienced at the hip joint during the activity. The hip joint is responsible for transmitting forces from the lower body to the trunk and upper body, making it crucial for overall movement and stability.
5. PFJ (force at patellofemoral joint) = 5 BW:
The force at the patellofemoral joint is 5 times the body weight. This value represents the load experienced at the knee joint between the patella

(kneecap) and femur (thigh bone). The patellofemoral joint is involved in various knee movements, such as knee flexion and extension, and plays a vital role in knee joint stability.

The interpretation of the results suggests that during the peak joint contact forces in this specific activity or exercise, the hip joint experiences the highest force (9 BW), followed by the total force (6 BW) acting on the entire joint system. The lateral tibiofemoral joint experiences the lowest force (2 BW) among the joint regions. The specific force values provide valuable insights into the distribution of forces across different joint regions, helping to understand the loading patterns and potential implications for joint health and performance during the activity.

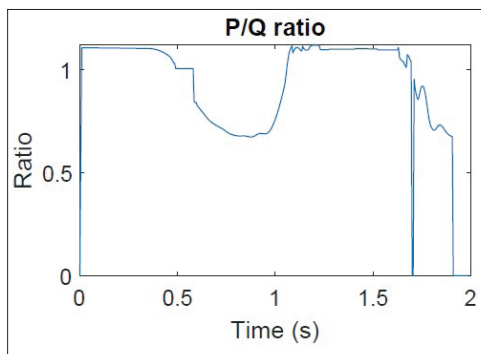


Figure 11: Simulated ratio of patellar tendon to quadriceps tendon force with respect to time from resting state to activity state.

The PQ ratio vs. time plot demonstrates dynamic changes in the balance of forces between the patellar and quadriceps tendons during different phases of the activity. The variations in the ratio indicate how the tendons work together to stabilize the knee joint and control movements throughout the activity. The ratio values and patterns can provide valuable information about the functional efficiency of the knee joint and the coordination between the patellar and quadriceps tendons during the specific activity being analysed.

Ergonomic optimization:

The results outline that key parameters to achieve the ergonomic compatibility in the knee joint support apparatus are load distribution, joint stability, customization, apparatus dimensions, material selection and dynamic balance. The parameters have interlinked

relation to actively control the ergonomic factor.

1. Load distribution: Ensuring that forces at critical joints like the hip (9 BW) and patellofemoral joint (5 BW) are appropriately managed to prevent excessive stress and potential injury.
2. Joint stability: Designing the brace to provide adequate support to stabilize the knee joint, particularly during movements such as flexion and extension, to mitigate instability and enhance overall joint function.
3. Customization: Utilizing 3D scanning technology to tailor the brace to individual anatomies, ensuring optimal fit and comfort while maintaining effectiveness in supporting joint mechanics.
4. Material selection: Choosing materials with appropriate stiffness and flexibility characteristics to provide support while allowing for natural movement, thus minimizing discomfort and maximizing user compliance.
5. Apparatus dimensions: Appropriate customized component dimensions improve ergonomics to the user.
6. Dynamic balance: Considering the dynamic balance of forces between the patellar and quadriceps tendons, as indicated by the PQ ratio over time, to optimize functional efficiency and coordination during various phases of activity.

The results of this study provide valuable insights into the biomechanics of the knee joint and hip muscles during specific activities. The analysis of knee joint forces reveals dynamic changes in force distribution and loading patterns across different joint regions, including the medial and lateral tibiofemoral joints, hip joint, and patellofemoral joint. The observed peaks and fluctuations in joint contact forces highlight the importance of joint stabilization and the potential implications for joint health and performance. Additionally, the investigation of the patellar tendon to quadriceps tendon force ratio sheds light on the dynamic balance of forces between these tendons during different phases of activity, providing valuable information about the knee joint's functional efficiency. Understanding these muscle forces and joint contact dynamics is crucial for designing effective rehabilitation protocols, injury prevention strategies, and optimizing movement patterns for improved performance and reduced risk of joint injuries. The function of a spring supported knee support brace on knee joint muscles in movement stabilization and performance improvement, relevant to a clinical setting, was validated by Dzidotor *et al.* (2023). The outcome of the present work, which specifically focuses on spring loaded active knee braces, is in coherence with the findings of Dzidotor *et al.* (2023) on general unloader spring supported knee braces.

The clinical application of these findings lies in informing rehabilitation protocols and injury prevention strategies tailored to specific activities. Understanding the distribution of forces across different joint regions, particularly at the patellofemoral joints, aids in designing interventions to mitigate potential joint overloading and instability. Furthermore, insights into the dynamic balance of forces between the patellar and quadriceps tendons during activity guide the development of targeted approaches for enhancing knee joint stability and functional efficiency. Further research and clinical applications based on these findings can enhance our understanding of the musculoskeletal system's intricacies and inform targeted interventions for individuals engaging in various physical activities.

CONCLUSION

The assessment of ergonomics and gait analysis of the knee joint model validates the usability of the system for effectively supporting the load on the human knee mechanism. The support system can be further validated through clinical trials to assess its viability for use in clinical scenarios for the prevention and management of musculoskeletal diseases.

In conclusion, the findings from the study present a comprehensive analysis of knee joint forces and hip muscle activations during specific activities. The plots of joint contact forces over time reveal the dynamic nature of force distribution across various joint regions, providing valuable insights into loading patterns and potential implications for joint health. The patellar tendon to quadriceps tendon force ratio analysis sheds light on the balance of forces between these tendons during different phases of activity, offering valuable information about knee joint stability. The results contribute to our understanding of the biomechanics of the musculoskeletal system and can guide the development of targeted interventions for optimizing movement patterns and reducing the risk of joint injuries. Further research and clinical applications based on these findings hold the potential to improve rehabilitation protocols, injury prevention strategies, and overall performance for individuals engaged in physical activities.

Conflict of interest

The authors have no conflict of interest to declare.

Ethical approval

There are no animals or humans involved in this study. Hence ethical approval is not applicable.

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