REVIEW ARTICLE

Associated factors of mechanical stress on the knee joint during walking in patients with knee osteoarthritis

Takanari KUBO,[1] Ryota IMAI,[1] Yuya MAWARIKADO[2]

[1]Department of Rehabilitation, Osaka Kawasaki Rehabilitation University, [2]Department of Medical Biology of Thrombosis and Haemostasis, Nara Medical University
Correspondence: Takanari Kubo, RPT, PhD, 158 Mizuma, Kaizuka City, Osaka, 597-0104, Japan.
E-mail: kubot@kawasakigakuen.ac.jp
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Abstract
Knee osteoarthritis affects a large number of people in Japan, so prevention and therapeutic intervention is important. Management and evaluation of knee osteoarthritis are therefore necessary. In recent years, with the advancement of 3D gait analysis technology, many studies have been conducted on factors related to mechanical stress during gait. We reviewed the factors related to mechanical stress during gait from a biomechanical perspective. We focused upon knee adduction moment and knee joint compression force, mechanical load indicators that utilize 3D gait analysis, and musculoskeletal simulation technology, and outline the current knowledge and treatment strategies. Studies reported in the literature are mostly of basic research and have not been derived from clinical practice. Clinical research utilizing these technologies will hopefully lead to the development of more evidence-based prevention and treatment interventions for knee osteoarthritis.

INTRODUCTION

Knee osteoarthritis (KOA) affects 50.3% of people in Japan aged 40 years or older, (Yoshimura, 2010) and approximately 300 million people worldwide (Sabha, 2022). KOA is a cartilage degeneration-based joint disease that causes knee joint pain, functional decline, deformity, and decrease of walking ability. Furthermore, it has been suggested that KOA significantly reduces health-related quality of life in terms of physical function (Muraki, 2010). In Japan, where the population is aging, the prevalence of KOA is high, and the disease is a cause of frailty and prompts the need for nursing care. In addition to anatomical factors such as cartilage thickness (Wieland, 2005) and subchondral bone mineral density (Clarke, 2004; Lo, 2006), there have also been reports of mechanical stress during walking. In addition to anatomical factors such as subchondral bone mineral density (Clarke, 2004; Lo, 2006), mechanical stress during gait is one of a number of factors associated with progression of KOA (Favre, 2016).

Excessive mechanical stress on the knee joint during gait contributes to KOA. Mechanical stress can be divided into compression, shearing, and stretching forces (Figure 1). Among these, excessive knee joint compression force (KCF) has been reported as a risk factor for KOA (Bennell, 2011). Evaluation and management of KCF is therefore an effective method of prevention and conservative treatment of KOA. However, measurement of KCF is not possible except by invasive methods, such as by implantation of a strain gauge in the knee joint.

In recent years, there has been development of indices reflecting KCF and based on noninvasive 3D gait analysis. In this paper, we summarize our research on 3D gait analysis and methods of calculating mechanical load indices using musculoskeletal simulation technology and their related factors, and we outline the treatment strategies and future prospects.

MODEL OF KOA AND MECHANICAL LOADING DURING WALKING: INTEGRATED JOINT SYSTEM

The integrated joint system (IJS) model has been proposed in consideration of the relationship between KOA and mechanical loading (Edd, 2018; Figure 2). The IJS model is a homeostatic state in which cartilage thickness, mechanical stress during motion, and subchondral bone mineral density of the knee joint adapt to each other, and the knee joint can remain healthy.

Among healthy subjects, those with relatively great loading at a particular site, as measured mechanically during gait, tend to have thicker cartilage

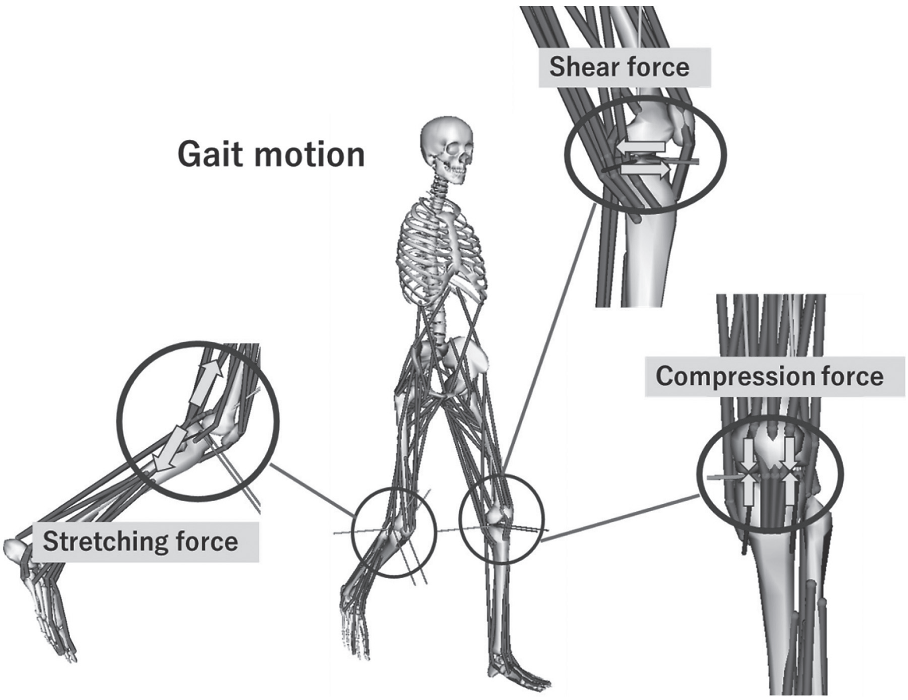

Figure 1. Mechanical stress on the knee joint during walking
The knee joint is subjected to compressive, shearing, and stretching forces during walking. Compressive and shear forces are believed to contribute to cartilage damage. Stretching forces mostly affect ligaments and soft tissues.

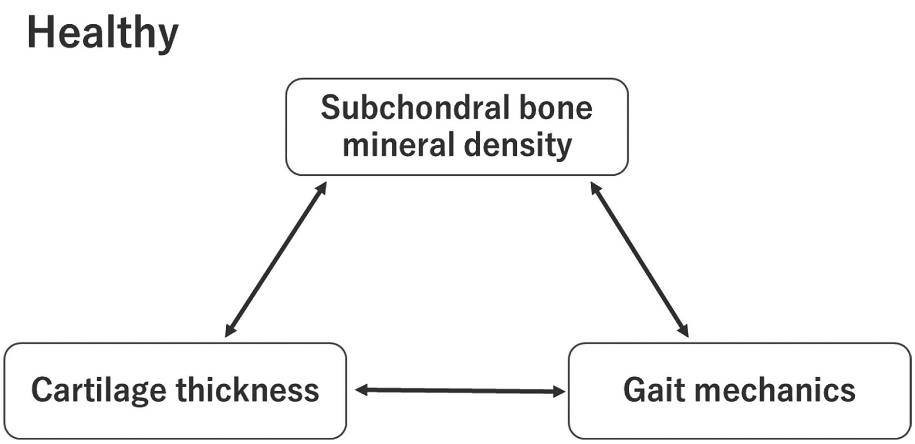

Figure 2. Integrated joint system (IJS)
IJS is the idea that the knee joint can remain healthy as long as the cartilage thickness, mechanical stress during movement, and subchondral bone mineral density are homeostatic and adapting to each other (modified quote from Edd SN, et al. Osteoarthritis Cartilage 26(11), 1425-1437, 2018).

at the same site (Schmitz, 2017). Healthy cartilage is suggested to adapt in response to certain gait mechanics, for example, cartilage in areas of high mechanical stress tends to become thicker. On the other hand, a negative correlation between cartilage thickness and mechanical stress has been shown in patients with KOA (Maly, 2015); this may be the result of a subject with thin cartilage being subjected to loading with strong intensity, which can lead to cartilage failure. Thus, for example, strong mechanical stress in a young subject without cartilage degeneration does not necessarily lead to KOA. As a preventive or conservative treatment method for KOA it is therefore effective to evaluate the subject's KCF and to manage it not only by decreasing the KCF, but also by determining the extent to which KCF can be increased, depending on the subject's condition.

MARKER OF MECHANICAL STRESS ON THE KNEE JOINT DURING GAIT

As mentioned above, it is difficult to measure mechanical stress on the knee joint. 3D gait analysis is mainly an optical method in which reflective markers are attached to landmarks on the body surface and are photographed by an infrared camera. Musculoskeletal simulation is an analysis technique that simulates motion using ground reaction force data in addition to marker trajectories obtained by 3D gait analysis. This paper focuses on KCF, knee adduction moment (KAM), and knee joint rotation moment (KRM) as indices of mechanical stress on the knee joint that can be validly calculated using 3D gait analysis and musculoskeletal simulation technology.

Knee joint compression force

Musculoskeletal simulation technology has made great progress in recent years. Musculoskeletal simulation analysis can quantify the relationship between muscle force and joint motion, etc., and can show the mechanical relationship between muscle and motion. For joint loading, it is now possible to dynamically calculate accurate KCFs, including muscle tension during movement in vivo, which is not normally measurable (Figure 3; Delp, 2007). In another demonstration of the usefulness of musculoskeletal simulation techniques, the amount of internal loading on the knee joint and muscle activity during gait obtained using these techniques differed between normal subjects and patients with KOA (Richards, 2010). A recent systematic review concluded that the KCF calculated by musculoskeletal model analysis better reflects the mechanical loading on the knee joint than the KCF calculated by knee adduction moment (KAM) and musculoskeletal model analysis (Holder, 2020).

Models with joint morphology specific to each subject have also recently begun to be used. KCF was calculated in a model reflecting subject-specific knee joint morphology in post-prosthetic patients with KOA with built-in strain gauges and obtained values that approximated measured values (Lerner, 2015). However, most studies using KCF with musculoskeletal simulation are basic studies and there are still few clinical studies.

Knee adduction moment

KAM is the torque applied by an external force in the direction of adduction of the knee joint. Significant correlation has been shown with the tibio-femoral interosseous compression force measured in the implant after total knee replacement for 10 different activities, including walking, stair climbing, standing, sitting, squatting, and one-legged standing (Trepczynski, 2014). KAM has therefore been the most commonly used simply-measured assessment as a valid marker to reflect KCF during motion.

For patients with KOA, KAM is related to knee joint pain (Amin, 2004) and radiographic osteoarthritic changes (Miyazaki, 2002). The first peak of KAM reportedly significantly correlated with the total score of the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), a patient-based assessment of KOA, and the scores of stiffness and function

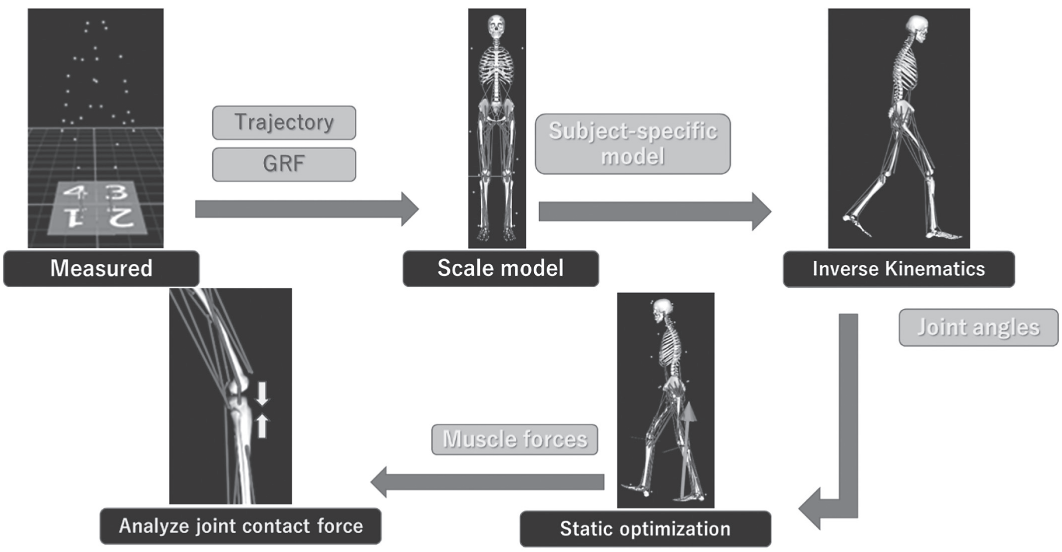

Figure 3. Process of musculoskeletal simulation analysis
Calculate KCF from marker trajectories and ground reaction force information obtained from 3D gait analysis through inverse kinematics, inverse dynamics, and static optimization analysis.

(Hurwitz, 2002). Furthermore, higher KAM during gait in KOA patients was associated with the degree of long-term subchondral bone and cartilage damage (Bennell, 2011). Research on the relationship between KOA and mechanical loading has therefore made significant progress since the utility of KAM was first reported.

Invasive treatments, such as high tibial osteotomy and knee arthroplasty, are treatment modalities that reduce the load on the medial compartment by altering the alignment of the subject's knee joint, thereby reducing the distance between the ground reaction force projection line and the knee joint, or the knee joint lever arm on the frontal plane. Many studies on clinical symptoms and KAM changes before and after these surgeries have reported good postoperative improvement (Lind, 2013; Sosdian, 2014). This is consistent with the mechanical changes due to surgical alignment correction and improvement in clinical symptoms, suggesting that surgical therapy is a causative treatment that decreases mechanical stress. In contrast, there are still few reports that show that exercise therapy reduces KAM.

The validity of KAM has also been suggested to be problematic because it depends on the subject and the movement task: KCF is composed of about 50% each of the effects of gravity and muscle forces (Saxby, 2016), and KAM can only reflect the effects of gravity. If patients with KOA walk with knee joint stiffness, for example, there could be greater muscle activity (Na, 2019) and increased pressure due to muscle forces than walking normally. KAM cannot therefore reflect changes in KCF due to muscle function, which is the target of rehabilitation therapy. In other words, the method using KAM cannot capture the mechanical load on the knee joint, which is a kinematic factor including the force generated by muscle contraction.

Knee joint rotation moment

CT examinations and three-dimensional gait analysis were performed on patients with KOA to calculate bone density of subchondral bone and KAM, KCF, and KRM. The less subchondral bone, the significantly higher the KRM was during gait (Roberts, 2018). Shear force, expressed as KRM, is therefore thought to be an important factor for OA changes in subchondral bone. Although the literature is currently very limited, further investigation is expected in the near future.

FACTORS RELATED TO MECHANICAL LOADING IN PATIENTS WITH KNEE OSTEOARTHRITIS AND TREATMENT STRATEGIES

Cases with foot abnormalities

Abnormal foot alignment and poor foot function may contribute to KOA by increasing mechanical stress on the knee joint during motion. Flatfoot morphology was determined to be significantly correlated with the degree of cartilage damage in the tibiofemoral joint based on MRI findings, suggesting that foot alignment and function may be connected and

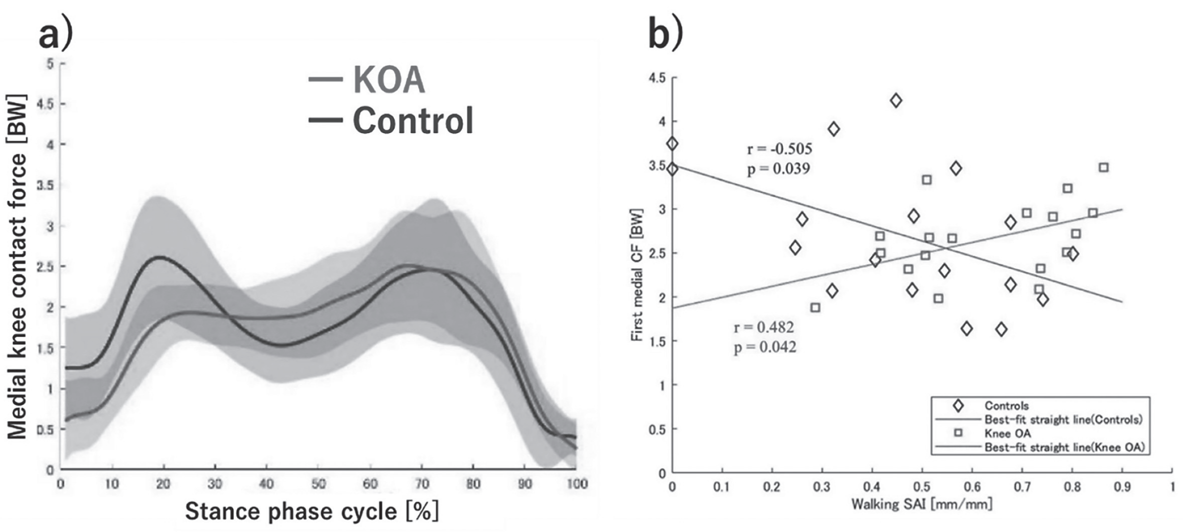

Figure 4. Relationship between KCF and foot morphology in patients with KOA and in healthy subjects
a) KCF of patients with KOA and healthy subjects in the ambulatory stance phase
b) Relationship between foot morphology and KCF
CF; Contact force, SAI; Staheli arch index (adapted from Kubo T, et al. BMC Musculoskeletal Disorders 23, 660-660, 2022)

that there may be a link with the development of OA (Gross, 2011). Meanwhile, while flat feet (Reilly, 2006), clubfoot (Levinger, 2010), hallux valgus (Golightly, 2015), and decreased toe grip strength (Uritani, 2017) reportedly occur in patients with KOA, few reports have biomechanically demonstrated such a relationship between these conditions and KOA. The relationship between foot morphology and KCF calculated by a foot manometer was studied in 18 patients with KOA and 18 healthy subjects (Kubo, 2022). KCF was calculated using the musculoskeletal model, which has 92 Hill-type muscle–tendon units with 23 degrees of freedom of the patients with KOA that reflected the subjects' knee joint alignment from the radiographs obtained during the clinical evaluation. The KCF during the stance phase of gait for each group is shown in Figure 4; it was bimodal, with peak values designated as the first peak and the second peak. The medial arch was lower in patients with KOA than in normal subjects, and the first peak of KCF was higher in those with a lower medial arch (Figure 4 b). This may be due to the medial displacement of the center of pressure (COP) as the arch decreases and the distance between the ground reaction force projection line and the knee joint center increases. In this case, interventions to increase the medial arch of the foot, such as training the tibialis posterior muscle, may prevent arch reduction and increase KCF.

Gait modification for mechanical stress reduction

The KAM is calculated as the spatial relationship between the center of the knee joint and the ground reaction force projection line from the COP on the forehead plane toward the body's center of gravity, or the length of the knee joint lever arm (KLA). The KAM of patients with KOA is at its maximum when the knee joint lever arm is at its greatest. The KLA of patients with KOA is at its lowest at the time of maximum KAM, indicating that the KLA of the knee joint is at its lowest when the COP and center of gravity are closer to the knee joint and the ground reaction force is lower. Interventions on the lever arm are thus thought to be effective in managing KAM (Hunt, 2006).

A systematic review was conducted on gait modification strategies to reduce KAM (Simic, 2011). According to the 24 articles that met inclusion criteria, KAM was decreased by use of a walking cane on the contralateral side, increased stride length, increased hip internal rotation angle, and increased lateral flexion angle of the trunk to the target side. Widening of hip internal rotation and lateral flexion of the trunk to the target side can bring the body's center of gravity closer to the knee joint, thus reducing the lever arm. However, the amount of modification and clear post-intervention effects were not mentioned in the review, and further research is required.

Orthotic therapy for KCF reduction

In a meta-analysis of 17 papers, it was reported that KAM during gait can be reduced by using valgus knee bracing (Moyer, 2015). This is done by inhibiting the adduction motion of the knee joint during gait and preventing the knee joint from displacing outward, thereby bringing the knee joint closer to the ground reaction force projection line. This may be because the lever arm can be shortened as a result.

In addition, a biomechanical study of patients wearing ankle foot orthoses for KOA reported that the lateral lower leg frame and plantar plate fixate the subtalar joint, causing the COP to be deflected outward (Menger, 2016). The COP is defined as the point of action of the ground reaction force, so the lever arm of the knee joint adduction moment shortens as the ground reaction force vector moves outward. Interventions to change the knee joint and COP position using orthotics and to make the decreasing KAM are thought to be effective.

CONCLUSION

In this paper, we outlined the current knowledge and treatment strategies for KOA with a focus on KAM and KCF, mechanical load indicators that utilize 3D gait analysis and musculoskeletal simulation technology. However, most studies to date have been basic research and are not derived from clinical practice. Clinical research utilizing these technologies will hopefully lead to the development of more evidence-based prevention and treatment interventions for KOA.

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