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Programvezető: Dr. Szendrői Miklós, egyetemi tanár

Témavezető: Dr. Kiss Rita, egyetemi tanár

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THE EFFECT OF DIFFERENT EXPOSURES OF KNEE ARTHROPLASTY ON STEPPING PARAMETERS, VARIABILITY OF GAIT DURING STEPPING AND DYNAMIC STABILITY IN THE EARLY POSTOPERATIVE PERIOD

PhD thesis

Ákos Pethes

Rácz Károly Clinical Studies Doctoral School

Semmelweis University

Supervisor:	Rita M. Kiss, D.Sc
Official Supervisor reviewers:	István Böröcz, MD, Ph.D Tamás Terebessy, MD, Ph.D
Head of the Complex Examination Committee:	Ákos Zsembery, Ph.D
Members of the Complex Examination Committee:	Zsolt Vendégh, Ph.D Gergely Holnapy, Ph.D

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LIST OF ABBREVIATIONS

ANOVA = ANalysis Of VAriance: statistical method to find out if experiment results are significant, in other words testing groups to see if there is difference between them
BMI = Body Mass Index
CAS = Computer Assisted Surgery
CV = Coefficient of Variance
D = Lehr’s damping ration
KL = Kellgren–Lawrence radiographic osteoarthritis grading system
KSS = Knee Society Score
MIS = Minimally Invasive Surgery
MP = Medial Parapatellar
OA = Osteoarthrosis
OKS = Oxford Knee Score
QS = Quadriceps-sparing
QOL = Quality of Life questionnaire
SF-36 = Short Form-36 (Quality of Life questionnaire)
TKR = Total Knee Replacement
VMO = m. Vastus Medialis Obliquus
WHO = World Health Organization
WOMAC = Western Ontario and MacMaster University (Quality of Life questionnaire)

1. INTRODUCTION

1.1. Choice of topic

Articular cartilage damage in the knee (osteoarthritis; OA) is one of the most common musculoskeletal disorders worldwide, affecting 30-40% of the population over 65 years of age. It is the primary cause of disability and reduced mobility in the elderly and is a significant economic burden on society (*Skinner, 1984*). Other data suggest that 9% of men and 18% of women suffer from knee OA (*Davis, 1991*). Fall-related injuries are the primary cause of accidental deaths over 65 years (*Sterling, 2001*). Most of these falls occur during a change of location. (*Niino, 2000*). Each year, more than one-third of adults over 65 years of age fall at least once (*Kang, 2007*). The prevalence of knee OA increases with age, and because of the ageing of population the burdens of the disease grow at an increased rate. Knee OA not only causes pain but is also associated with limited mobility and deterioration in the quality of life (*Lee J, 2015*). These symptoms significantly limit the ability to get up from a chair, stand comfortably and walk on a flat surface or stairs (*Kaufmann, 2001*).

The number of total knee replacement (TKR) implantations is increasing year by year both in worldwide and in our country. After surgery, pains are significantly relieved, and the previously weakened skills and motor functions are partially or fully restored. In addition, timely surgical intervention and rapid rehabilitation improve the patient's self-care and ensure an eventual return to work, thereby reducing the financial burden on both the healthcare system and society. In addition, health care institutions in developed countries put an ever-increasing emphasis on assessing and monitoring the patient's condition in order to record the course of treatment, the effectiveness of surgical care, and rehabilitation. This is done using pain scales, quality of life questionnaires, and tests in daily clinical practice. One of the oldest questionnaires for pain assessment is the Visual Analogue Scale (VAS). Joint-specific questionnaires, recording certain body regions focusing on specific joints, are widely used to record the knee joint function. These include the American Knee Society Score (KSS) (*Insall, 1989*) or the Oxford Knee Score (OKS) (*Dawson, 1998, 2010*). When using the above methods, the objectivity of the status recording is unlikely to be reliable, in case of different investigators the reproducibility of the test is often questionable. A more accurate assessment of the condition can be obtained by using biomechanical methods and appropriately selected motion testing measurement systems, and by comparing the numerical data, changes in motion can also be statistically analyzed. In addition to static tests, motion testing analyzing systems are also suitable for recording dynamic deviations observed during motion, and the reproducibility of the motion test is also ensured. Biomechanical measurements are suitable to refine the severity classification of the disease and can record specific differences between individual patients. Then the data can be analyzed to tailor conservative treatment to improve musculoskeletal function and the surgical indications can be more exact. Human movement is influenced by a myriad of conditions, such as muscle function, posture, and the state of the motor control system. In healthy individuals, gait is a cyclical and symmetrical movement. It is insufficient to analyze gait patterns of patients when investigating the impact of degenerative joint abnormalities and the effect of implantation of lower limb endoprosthesis right after the operation. It is also necessary to define gait safety, as a reduction in gait safety may result in an increased risk of falls. The safety of walking is mainly determined by the regularity of gait and dynamic balancing ability. After TKR implantation, walking safety can be significantly improved, and walking ability can be almost fully restored to the age-appropriate level for the patient. It is important to select the right rehabilitation treatment. Close monitoring of functional improvement and appropriate therapeutic modification can lead to a successful and timely recovery. Knee osteoarthritis and TKR implantation significantly affect gait parameters, stability, and regularity of gait. In most cases, on a treadmill based gait analysis can only safely conducted at least three months after surgery. Thus, in the early postoperative period, gait parameters can only be tested using our stepping method. The primary objective of this study is to determine how TKRs implanted with different types of surgical exposure techniques affect kinematic parameters and two factors of gait safety, gait regularity and dynamic balance ability, in the postoperative period. Such biomechanical-based studies of the effect of TKR implantation in the early postoperative period are not yet available neither in the national and nor in the international literature. Motion testing is possible only while the patient is standing or stepping in the early postoperative period. The results obtained can be used to define the impact of joint endoprostheses implanted with different exposure techniques on gait more accurately, better understand specific compensatory mechanisms, design complex individualized preventive protocols and protocols for enabling faster rehabilitation as well as monitor the effectiveness of postoperative rehabilitation. Our work also aims to consider the benefits in the early stages of rehabilitation of a more precise prosthetic component insertion solution, which requires a more extensive toolset and a slightly longer surgical time even after the training period, but less tissue damage due to less exploration.

1.2. Literature review

1.2.1. Total Knee Replacement (TKR)

Total knee arthroplasty aims to restore the function of the painful, degenerated, osteoarthritic knee joint that can no longer be treated conservatively and can provide stable, pain-free movement. Compared to the hip joint, to restore its function with a prosthesis the knee joint biomechanically is much more challenging. It is much more difficult to understand and imitate the actual kinematics of the knee joint. Understanding the much more complex motion in different types of arthroses (varus, valgus, stiff rheumatoid arthritis, post-traumatic) has allowed the development of increasingly sophisticated prosthetic systems to better mimic and resemble physiological knee function. Thus, these improved designs can lead to improved functional outcomes *(Falez, 2016)*. Few areas have advanced more than the understanding of knee kinematics and knee arthroplasty in orthopedics. Surgical outcomes have shown an ever-increasing improvement in recent decades. Bejek, combining EMG examination with gait parameter studies, has shown that gait parameters measured during a one-year follow-up cycle following TKR implantation gradually approach those of a healthy control group. In cases where the patient’s affected extremity was the dominant one, the other, intact extremity becomes dominant. However, as time passes, the operated extremity once again shows gait parameter values consistent with the dominant side extremity *(Bejek 2009, 2011)*. The main pillars of development are computer-assisted navigation surgery, robotic surgery, and prostheses tailored for the patient. However, unfortunately, some of these operations are still unsuccessful, some patients continue to experience pain, and their mobility remains impaired. 20 % of patients are dissatisfied with the outcome of their knee replacement (*Confalonieri, 2019).* In some cases, additional surgery is performed, which at times still does not result in the desired improvement *(Causero, 2017).* Navigation, as most newly introduced technologies, has not yet proven to offer a significant advantage in knee replacement; nevertheless, more precise implant position due to a more accurate bone surface sculpting and better ligament balance both in flexion and extension may lead to longer implant life and overall greater patient satisfaction *(Falez 2016)*. However, other researchers have found that computer-assisted implantation offers no significant advantage in implant positioning, improvement in functional outcome, or increased subjective satisfaction (*Allen, 2014*). In addition, besides the not yet fully proven benefits, navigation surgery clearly takes longer and requires specialized and complex techniques, which may lead to additional complications (*Falez, 2016).* Also, studies by Bejek, cited earlier, show that rehabilitation after minimally invasive navigation-assisted knee replacements is significantly more advanced three months after surgery; however, this difference is no longer present six months after surgery (*Bejek, 2006, 2007, 2009, 2011).*

1.2.2. The balancing ability and its characterization

To maintain a balanced posture, i.e., maintaining the body's center of mass over its base of support, muscle tone adjustment in the antigravity muscles is under constant control, both at rest and during walking. In addition, information from somatosensory, visual, and vestibular receptors constantly modifies and coordinates posture *(Szirmai, 2017).* It is a process controlled by a dynamic feedback system, whereby a complex mechanism is used to record and track each movement, as well as to trigger and control coordinated muscle responses to ensure the ability to balance. The fundamental element of the ability to balance is proprioception, i.e., the ability to sense the parts of the body relative to one another. This means the conscious and unconscious perception of limb position in space, including the perception of joint position and movement. The central nervous system regulates the stabilization of the joint and the activation of the muscles around the joint, based on information sent by the somatosensory system (including the proprioceptive input signal), the balancing system, and the visual system. Knee proprioception is derived from the integration of afferent signals sent by muscles, tendons, articular capsules, ligaments, meniscal attachments, and skin receptors. The main sources of joint proprioception are muscle and joint receptors *(Sharma, 1999).* Rheumatological and orthopedic diseases can lead to static and dynamic changes in postural control. Reduced stability following arthrosis or ligament injury can lead to a reduction in the ability to balance the lower limb *(Missaoui, 2008*; *Quagliarella, 2011).* Freeman suggested (*Freeman, 1965*) that any effect on this complex regulation, such as wear of the articular surfaces, narrowing of the range of motion, or weakening of muscle strength, significantly affects the proprioceptive system. These effects also impact coordinated movement and the ability to maintain balance. The question is whether impaired proprioception increases the risk of knee osteoarthritis and whether it accelerates the progression of the disease *(Sharma, 1999).* We distinguish between static and dynamic balancing. The static balancing ability is based on the static reflex, which balances the body at rest, while the kinetic reflex, which is required for dynamic balancing, balances the body in motion. Dynamic balancing includes kinesthesia (muscle sensation, deep sensation), which is a type of sensation originating from proprioceptors in the muscles (tendons, fascia, articular capsules and ligaments). Proprioceptive sense plays a crucial role, providing continuous information about the position and movement of the limbs, torso, and head, and the current state and tension of muscles, tendons, and joints, in all types of movements including walking. *(Szirmai, 2017).* Previous research has made it clear that both static and dynamic balancing abilities are significantly affected by age *(Skinner, 1984; Prieto, 1996; Pai, 1997; Vandervoort, 2002; Vereeck, 2008; Boyer, 2019)* and sex of the person being tested (*Masui, 2005; Boyer 2019).* Proprioceptive ability, which declines with age, can be improved by regular exercise (e.g., tai chi chuan) (*Wong, 2001*), which can help reduce the risk of falls (*Petrella, 1997*). Six months after knee joint endoprosthesis implantation, patients' joint position sense is the same as that of healthy individuals of similar age (*Ischii, 1997).* This is probably because the condition of the ligaments and muscles around the joint has a much more significant influence on joint position sense than the condition of the articular surface *(Ischii, 1997).* On days 17-20 after knee joint endoprosthesis implantation, the area traversed by the center of pressure and its anterior-posterior and lateral movements were still significantly greater than those of the control group *(Gauchard, 2010).* By the 6th week after surgery, the standing stability values improve significantly but are still below those of the control group *(Gauchard, 2010; Dominguez-Navarro, 2018).* Six months after knee replacement, balance significantly improves compared to preoperatively when standing on an unstable platform on two legs (*Swanik, 2004*) and standing on a stable platform on both one leg and two legs *(Isaac, 2007).* By the 6th month after the surgery, the postural sway by the center of pressure measured while standing on the affected leg is significantly reduced compared to before the surgery, while the length of the trajectory is not significantly reduced *(Isaac, 2007).* Postural stability parameters (length of the center of pressure trajectory, area traversed by the center of pressure) measured while standing on both legs are significantly improved in the later postoperative period but are also significantly worse than those of the control group one year after surgery *(Quagliarella, 2011).*

When walking in everyday life, unexpected stumbles often occur. A particularly complex mechanism is needed to regain balance *(Winter,1995*); therefore, testing the balancing response to a sudden change is more important than testing balance while standing *(Kiss, 2011).* Loss of balance is strongly associated with the likelihood of falling *(Robbins, 1989).* The dynamic balancing ability can be well modeled by the ultrasound-based sudden change of direction test, as the dynamic balancing ability can be modeled by the Lehr damping ratio calculated from the measured data *(Kiss, 2011; Kiss, 2012).* Dynamic balancing ability in older adults is influenced by lateral dominance, age, and sex of the person tested *(Kiss, 2011; Kiss, 2012).*

1.2.3. The gait pattern and its characterization

Gait is a cyclical and symmetrical coordinated movement that occurs without effort. During gait, the whole body moves in a continuous, progressive motion due to the alternating movements of the lower limbs while maintaining the stability of the standing position. Each step sequence involves multiple interactions of the two multisegmented lower limbs and the trunk. The gait is cyclical due to the repetition of each phase, while its symmetry is due to the coordinated, intermittent movement of the two limbs in relation to each other. Gait is determined by the movements of the lower limbs but is also influenced by the coordination of the movements of the head, trunk, and upper limbs *(Mészáros, 2006).* The most widely used reproducible gait analysis methods for recording gait parameters are optical-based (video or infrared-based), electromagnetic-based, and ultrasound-based motion analysis systems *(Kiss, 2007).* One of the bases of gait analysis is the gait cycle, which is the total period of movement of a limb, i.e., the period between two identical positions of the same limb, defined as the period from the initial contact with the ground, in a healthy person, from the heel strike to the next contact of the same foot with the ground *(Barton, 1997*; *Ángyán, 2005).*

Kinematic parameters can be used to characterize the gait pattern: temporal (step duration, cycle duration, stance phase duration, swing phase duration, double stance phase duration) and spatial (step length, step cycle length, step width). Angular parameters are another set of often used kinematic parameters employed to characterize joint movements. The gait pattern can be objectively characterized by temporal, spatial, and angular parameters derived from gait analysis. Older women have higher rates of reduced mobility, which may be caused by gender-specific differences in gait and muscle function. In older, less active people, walking at a self-selected gait speed becomes unsteady, with a risk of falling, mainly due to weakness of the quadriceps muscles. Regular physical activity can reduce the adverse consequences of knee joint degeneration *(Boyer, 2019*; *Hafer, 2019ab).* Several investigators have presented the parameters describing the altered gait pattern of patients with knee joint wear: patients with lower limb, especially knee joint, osteoarthritis, have longer gait cycles, lower cadence, shorter step length, and slower speed compared with healthy subjects of the same age *(Sun J, 2017*; *Naili JE, 2019).* As a consequence of the degenerative knee joint abnormalities, the self-selected gait speed, step frequency, and the affected side stride length and stance phase duration decrease, while step width increases, compared to the values of the control group of the same age. The range of motion of the joint affected by OA is reduced (the range of motion of the knee joint angle on the affected side is reduced), but the range of motion of the opposite hip and knee joint angle is increased due to compensatory movements. These results confirmed that the gait of patients with knee joint wear is not symmetric *(Kaufmann, 2001*; *Bejek, 2006, 2007, 2009, 2011*; *Newell, 2007, 2008*; *Jenkyn, 2007*; *Astephen, 2008* ; *Heiden, 2009*; *Hunt, 2010*; *Creaby, 2012*; *Lee, 2013*; *Mills, 2013a,b*; *Kiss, 2011,2012*; *Tawy, 2018*; *Biggs, 2019 a,b*; *Mine, 2019*; *Kobsar, 2019).* The gait of patients with knee osteoarthritis adapts to reduce pain. The quadriceps muscles that influence knee movement are less active, and the dynamic load during gait is reduced. Furthermore, obesity, an increased risk factor for knee OA, compels patients to modify their gait to reduce joint stress (*Kaufmann, 2001).* Proprioception (the ability to sense changes in joint position) declines in both knees, even for patients with unicondylar OA affecting only one knee. No difference was found between the proprioception parameters of the two knees, despite the different extent of cartilage wear. It is a noteworthy observation that the loss of proprioception is independent of the degree of OA, and therefore Koralewicz et al. recommend comparing the changes after TKR implantation with the untreated contralateral knee instead of with same-age healthy controls *(Sharma 1997*; *Koralewicz 2000).* Other researchers have also found that in patients with knee joint wear, gait speed significantly affects spatial and temporal parameters, as well as knee joint and hip joint angle range of motion *(Bejek*, *2006*; *Möckel, 2003)*. Compensation also involves increased movements of the pelvis *(Bejek, 2006).*

Previous research has also analyzed the effect of TKR on gait patterns *(Ishii 1997; Walsh, 1998; Berth, 2002; Ouellet, 2002; Smith AJ, 2004; Bejek, 2006, 2007, 2009, , 2011; McClelland, 2007, 2009, 2011, 2017; Mandeville; 2008 Yakhdani, 2010; Hatfield, 2011, Orishimo 2011; Abbasi-Bafghi 2012; Kiss, 2012; Sosdian, 2014; Lee 2015; Baczkowicz 2018; Biggs, 2019 a,b; Agarwal, 2019)*. According to Skinner, the proprioceptive deficit caused by OA cannot be corrected by surgery (*Skinner, 1984*). In contrast, Barrett argues that by restoring the joint alignment and "joint space height" with the collateral structures retightened, postoperative joint position sense is improved. Accurate adjustment of soft tissue balance (in terms of posterior cruciate ligament and collateral ligament tension) in both flexion and extension is essential for proper postoperative knee joint proprioception. *(Barrett, 1991; Moutzouri, 2016).* Isaac et al. also found a definitive improvement in static and dynamic proprioception after TKR *(Isaac, 2007*). The spatial parameters of gait gradually improve beginning postoperative week six; however, they do not reach the values of the healthy control group using either surgical approach. (*McAndrew, 2010, 2011).* Significantly lower gait speeds, longer dual stance phase durations, and shorter step lengths are observed at this time. Testing gait speed is difficult, and the often-used questionnaire method is inaccurate because patients overestimate their own performance as pain decreases. Objective measurement of gait speed is problematic due to differences in the environment, the measurement methodology, and instructions given to the subjects (*McAndrew, 2010, 2011; Abbasi, 2012).* A further difficulty is that 80% of patients with knee OA also have at least one type of comorbidity, so the homogeneity of the groups is questionable (*Abbasi, 2012).* Studies on function conducted more than two decades earlier report very poor functional outcomes even after the postoperative 12th month despite significant pain reduction *(Walsh, 1998).* Following the currently used TKR, the self-selected comfortable walking speed, cadence, step width, and stride length approximate but do not reach the values of the control group *(Berth, 2002; Lee, 2015).* The improvement is more specific to the adjacent hip and ankle joint function (*Moutzouri, 2016; Biggs, 2019*). Despite these improvements, the joint movements on the affected side are restricted. Even after a clinically well-functioning TKR, the asymmetry between the two knees is visible to the naked eye at self-selected gait speed. This is presumably due to a pain avoidance strategy, those adaptive or compensatory mechanisms that persist after surgery and that significantly affect and load the healthy, large contralateral lower limb joints. In previous publications of our research group (*Bejek, 2006*), we have shown that after TKR, the coordination of the surrounding muscles and the movement of the joints of the contralateral limb are significantly altered. During walking, the movement abnormalities caused by the damaged joint are compensated by increased flexibility in the collateral joints and pelvis. The patients' painful antalgic gait, reduced range of motion, axial deformity, and possible joint instability can lead to asymmetric movement. This is clearly supported by gait studies (*Walsh, 1998; Ouellet, 2002; McClelland, 2009; Hatfield, 2011; Lee, 2015; Biggs, 2019).* In addition to the angular differences, differences in kinetic parameters can be observed when comparing the prosthetic side with the normal side, which can be explained by the presence of compensatory mechanisms that have developed prior to surgery. After TKR, the patient's ability to walk can improve significantly, and over time the patient's average walking ability can be almost fully restored to age-appropriate levels *(Bejek, 2009, 2011).* An interesting observation on gait speed is that after 12 months, improvement may stop and is followed by decline again due to the increasing impact of comorbidities (*Abbasi, 2012).* According to Bejek's observations, the measured gait parameters gradually approach those of the healthy control group over a one-year follow-up cycle. If the affected side was previously the dominant side limb of the patient, the role of the affected side is taken over by the intact opposite limb. However, this will change over time, and after a while, the operated limb will again show the gait parameters of the dominant limb *(Bejek, 2009, 2011).* However, gait tests can only be used beginning three months after surgery, so there is little quantitative information available on the first few weeks after surgery to assess the earliest possible rehabilitation. In the early postoperative period, it is particularly important to check the patient's balance while walking; therefore, it is essential to perform the tests not only on a fixed, stable but also on a non-fixed plate. R. M. Kiss developed a complex measurement method that allowed the determination of the most important biomechanical parameters of gait while observing the patient stepping on a fixed and a non-fixed plate. The great advantage of this method is that patients can be examined in the early postoperative period *(Kiss, 2007 a,b).* Using a ZEBRIS gait tester, Bejek found that gait speed can affect gait parameters. By examining gait at different speeds, he found that if the gait test is performed at the same speed between 2-5 km/h, the ZEBRIS can provide reproducible, traceable, and reliable measurements of gait parameters (*Bejek, 2009*). Our previous study demonstrated that the effect of TKR performed using the two different types of surgical techniques is not the same on gait characteristics (spatial, temporal, and angular) in the early postoperative period. The study results clearly demonstrated that the different surgical techniques, which also differ in terms of invasiveness, significantly affect the kinematic characteristics of stepping (the variability of knee motion and the angular parameters of pelvis and shoulder joint tilt and rotation) *(Pethes, 2014).* The stepping parameters of patients who underwent surgery using navigation with less invasive techniques improved more quickly than patients who underwent conventional surgery; however, neither reached the values of the control *(Pethes, 2014).*

1.2.4. Characterization of the variability of the gait

The kinematic characteristics of the gait vary with each step, even under the same external conditions. The constant variation of the parameters determines the gait variability. The fluctuation of the gait parameters determines the variability of the gait: the variance of the spatial, temporal, and angular parameters of the step cycle *(Dingwell, 2006; Kang, 2008 a, b; Owings, 2003, 2004; Dubost, 2006; Hollman, 2007 a,b; Jordan, 2007; Kiss, 2012*). If the spatial and temporal variables are nearly the same for each step, and the phases of the gait repeat exactly, we speak of harmonious walking (*Mészáros, 2006).* According to Owings and Grabiner, at least 400 step cycles are required to calculate gait variability because the spatial and temporal variance does not change significantly after this number of step cycles. A lower count may produce erroneous results (*Owings, 2003).* The tests were conducted both at a self-selected comfortable speed and at a slower or faster speed of walking than comfortable. They found that similarly to healthy young people, the temporal and spatial variance and relative variance were significantly influenced by the walking speed of healthy older people *(Kerrigan, 2001; Shkuratova, 2004; Dubost, 2006; Jordan 2007, England, 2007; Beauchet, 2007, 2009; Jordan, 2007; Kang, 2008ab; Kiss, 2012*). Owings' research shows that gait speed does not affect gait variability. Gait variability can be tested simply on the normal ground at a self-selected speed *(Hollman, 2007)* or on a treadmill at a self-selected or slower or faster speed *(Owings, 2003, 2004; England, 2007; Kang, 2008 a, b).* Fall-related injuries in older people are one of the biggest healthcare challenges. An increase in gait variability is proportional to an increase in the risk of falling. *(Hausdorff, 1997, 2001; Maki, 1997; Kang, 2007).* Older adults walk more slowly, and their gait variability exceeds that of younger adults. By reducing the walking speed, young people's gait variability also increases. However, it is unclear whether the more irregular gait observed in older people is due to age-related neuromuscular decline (*Kang, 2008 a, b*), weakened muscle strength (*DeVita, 2000*), or reduced mobility (*Kerrigan, 2001*). Step width variability is greater in older people (over 65) than in younger people *(Owings, 2003, 2004, Kang, 2007, 2008).* It was previously thought that by reducing gait speed (as when healthy individuals slow down before to move across the icy surface), gait stability could be increased *(Winter, 1990, 1995).* Paradoxically, however, slower walking speeds result in greater variability of the walking parameters, leading to a loss of stability *(Kerrigan, 2001; Kiss, 2010).* It is unclear whether the reduced gait speed of elderly patients with reduced joint range of motion and kinetics is the cause or the effect of these biomechanical changes *(Dingwell, 2006).* Understanding how walking speed affects dynamic stability can help to resolve this paradox. Stability can be defined as the capacity of the locomotor system to respond to perturbations *(Dingwell, 2006).* A reduction in gait regularity, or, in other words, increased variability, can be a good predictor of the likelihood of subsequent falls *(Maki, 1997; Hausdorff, 2001 a, b).* These measurements do not accurately indicate the response of the neuromuscular system to disturbances, stumbles, or slips. Thus, stability cannot be measured accurately. It has been observed that various neurological diseases (e.g., Parkinson's disease, Alzheimer's disease, dementia) affect step length and step width as well as step duration in parallel with deterioration *(Blin, 1990; Schaafsma, 2003; Hausdorff, 2005; Herman, 2005).* However, other studies have also shown that gait variability, even in healthy individuals, depends on the current psychological and cardiovascular state *(Hausdorff, 1994, 2005)* and the testing environment (*Hollman, 2006).* Studies have confirmed that age also significantly affects gait variability (*Kang, 2008 a, b).* When comparing the variability of gait parameters in healthy young and healthy elderly individuals, researchers observed that gait becomes less adaptable to changing conditions with age due to deteriorating balance and a relative lack of sufficient muscle strength to step over obstacles (*Buzzi, 2003; Kang, 2008 a, b*). Dingwell, therefore, suggests adjusting the walking surface, i.e., using "perturbations" that mimic an irregular surface, to better model the risk of falls in the elderly while walking *(Dingwell, 2007).* Younger adults were able to increase their dynamic stability by reducing their walking speed, but the same could not be said for older adults, who typically walk more slowly, and for whom a reduction in walking speed does not reduce the risk of falling. This also explains the more frequent falls in older age. *(Kang, 2008 a, b)* To increase local dynamic stability, the neuromuscular system that controls gait can adapt to a slightly irregular gait during slower gait (*Dingwell, 2004; Kang, 2008a*), but the relationship to this in terms of whole-body stability is not yet clear.

2. OBJECTIVES

2.1. Aims

The aim of the study is to compare and analyze the kinematic parameters of stepping, variability of stepping, and balancing ability after a sudden change of direction in patients suffering from unilateral knee joint destruction who underwent knee replacement implantation using two different surgical methods (conventional and minimally invasive computer-assisted navigation). An internationally recognized ultrasound-based motion testing method, previously developed by our research group, has made it possible to quantitatively describe the kinematic parameters of stepping, characterize stepping regularity (or, in other words, the opposite of variability) and dynamic balancing ability (ability to overcome unexpected obstacles). Based on the assessment of the research summarized in the previous chapter, we established the following objectives for our own research:

1. to determine the kinematic parameters of patients with unilateral advanced cartilage damage - knee OA - awaiting TKR; to describe quantitatively how these parameters change with different surgical techniques from the preoperative period until the end of the postoperative 3rd month in a longitudinal study; and, to compare the values thus obtained with those of healthy controls of similar age with no musculoskeletal complaints on a fixed plate,

2. to determine the kinematic parameters of patients with unilateral advanced cartilage damage - knee OA - awaiting TKR; to describe quantitatively how these parameters change with different surgical techniques from the preoperative period until the end of the postoperative 3rd month in a longitudinal study; and, to compare the values thus obtained with those of healthy controls of similar age with no musculoskeletal complaints on a non-fixed, moving plate,

3. to measure the variability of stepping parameters (knee motion, and the regularity of angular pelvic and shoulder joint tilt and rotation) in patients with unilateral advanced cartilage damage - knee OA - awaiting TKR on a fixed plate; to compare the variability of the preoperatively-measured stepping parameters with the parameters measured in the early postoperative period in the same patients; and to determine the extent to which the two

different surgical techniques, conventional and minimally invasive, affect stepping variability, and to compare the longitudinally followed changes in stepping variability with those of healthy age-matched controls with no musculoskeletal complaints,

4. to measure the variability of stepping parameters (knee motion, and the regularity of angular pelvic and shoulder joint tilt and rotation) in patients with unilateral advanced cartilage damage - knee OA - awaiting TKR on a non-fixed, moving plate; to compare the variability of the preoperatively-measured stepping parameters with the parameters measured in the early postoperative period in the same patients; and to determine the extent to which the two different surgical techniques, conventional and minimally invasive, affect stepping variability, and to compare the longitudinally followed changes in stepping variability with those of healthy age-matched controls with no musculoskeletal complaints,

5. To determine the extent to which different surgical techniques affect Lehr's damping ratio -- an indication of dynamic balancing ability that is closely related to the incidence of falls in old age as measured by the ultrasound-based sudden change of direction test (hereafter referred to as the provocation test) - in the preoperative and the first three months of the postoperative period; and to compare provocation test scores taken at different times during the perioperative period with the mean of Lehr's damping ratio of the healthy controls of similar age with no musculoskeletal complaints.

2.2. Materials and Methods

2.2.1. Participants

The control group (Group I) consisted of five voluntary women and men (age: 70.4±6.22 years, body mass: 71.6±15.43 kg, body height: 168.8 cm±11.71 cm) (Table 1). These people/subjects had no history of OA of the knee or hip joints, spinal deformities or clinical history of other musculosceletal disorders affecting their lower limb or lumbar spine (e.g. knee instability or major lower extremity surgery). These individuals had normal strength, full range of motion of the lower extremities and had no neurological alterations (e.g. Parkinson’s, dementia, vertigo or cerebral apoplexy, etc.) or vestibular disorders that may influence the balance. In order to perform the biomechanical tests safely, patients with uncontrolled or not properly maintained cardiovascular diseases (hypertension, unstable angina) or patients needing greater than ±5.0 dioptres correction of the vision were excluded.

Twenty patients with severe knee OA associated with pain and limited range of motion were included in our study from the waiting list for TKR who had already no or minimal response to conservative treatment. Each patient had less than 15° varus and less than 10° valgus axis deviation and had less than 15° flexion contracture. Each patient had unilateral symptoms (only one knee was affected). The exclusion criteria included any significant clinical history of lesion or surgery affecting the lower limbs or the lumbar spine. In order to perform our measurements successfully, each patient included was ambulatory, could walk without applying any assisting devices and had all the exclusion criteria that we already used in the case of the control group (Group I).

The severity of OA of the knee joint was determined by the Kellgren and Lawrence radiographic index (KL) *(Kellgren, 1957*) with the support of an expert in radiology (Dr. Köllő Katalin). The radiographic index was grade 4 in 16 patients and grade 3 in 4 patients. Patients underwent a physical examination and for each patient quality of life tests were also filled in before biomechanical tests. We used the functional test (0-100 point-scale) introduced by Insall (Knee Society Score, 1989) *(Ranawat, 1973; Insall, 1989),* the SF-36 questionnaire with its 36 questions about quality of life (0-100 points) (*Hill, 1999*) and the WOMAC-scale which is specific in joint deterioration (0-96 points) *(Bellamy, 1995).*

The 20 patients, who had no significant differences in antropometry, functional tests and in the grade of OA, were randomly and equally allocated into two groups based on the different surgical technique (Groups II and III).

Group II (conventional method: total anterior exposure with medial parapatellar incision) consisted of five men and five women (age: 66.6±7.45 years, body mass: 84.9±13.44 kg, body height: 168.9 ±10.25 cm).

Group III (minimal invasive technique: quad-sparing or mini-midvastus incision depending on the anatomical situation, with computer-assisted navigation) consisted of eight women and two men (age: 72.0±6.04 years, body mass: 72.3±12.56 kg, body height: 160.3±8.60 cm*).* All patients underwent TKR performed at the Orthopaedic Clinic of Semmelweis University, Budapest, Hungary. Computer-assisted surgery (CAS) was performed by the Stryker–Leibinger imageless navigation system.

In both patient groups, full weight bearing was started on the third postoperative day, and all patients were discharged within two weeks after surgery. Thus, all subjects had standard pre- and postoperative management (anaesthesia, pain management, physical therapy protocols).

Each subject examined was informed about the risks and benefits of the study and given the opportunity to withdraw from the study at any time. All patients gave their informed consent prior to the study. Patients underwent motion analysis before surgery as well as two, six and 12 weeks after TKR. Before performing the biomechanical tests each patient's physical status was invariably recorded by quality of life questionnaires and functional tests. The study was authorized by the National Science and Research Ethics Committee (184/2007).

2.2.2 Surgical exposures

2.2.2.1 Conventional exposure

In conventional exposure with the knee in a flexed position, a central straight cut is made at 2 cm from the patella base proximally, proceeding distally, as far as tibial tuberosity. It is recommended to finish the cut distally at 0.5-1 cm from the medial part of the tibial tuberosity in order to avoid harming the patellar tendon adhesion. The length of skin incision is dependent on the size of the knee and the patient's obesity (BMI). In vertical direction, cut is made as far as the fascia of the extensor musculature. There also exists a less recommendable medial patellar skin incision (*Sanna, 2013*) which leads to more vascular damage and may even cause the necrosis of lateral skin flap (*Sanna, 2013*). Standard arthrotomy of the joint with medial patellar incision in the flexed knee *(Insall, 1971; Ranawat, 1989; Sanna, 2013; Lotke 2019)*: the surgeon begins by cutting the quadriceps tendon longitudinally up to a point 1 cm from the vastus medialis obliquus (VMO), proceeding distally, cutting the medial patellofemoral ligament and medial capsule 5 mm from the medial border of the patella. Reaching the medial borders of the patellar tendon, the incision is guided distally, parallel to the patellar tendon, as far as the tibial tuberosity.

2.2.2.2 Tissue-sparing arthrotomies

Some authors *(Hofmann, 1991, Sanna, 2013)* have recently been led to the use less invasive arthrotomies; they assume that a reduction in the length of the surgical incision and of soft tissue damage will mean a better outcome in aesthetic and surgical terms, as well as in terms of pain and functional recovery. In particular, these approaches are proposed in order to avoid violation of the extensor apparatus and to keep it as intact as possible. The most commonly used are the subvastus approach, the midvastus approach and the trivector approach (*Sanna, 2013*).

The subvastus approach was first described in literature by Erkes in 1929 *(Erkes, 1929).* This approach was taken up again by Bechtol (*Bechtol, 1976*) in 1976 and by Hofmann in 1991 (*Hofmann, 1991*). Isolation of the extensor apparatus and the VMO: the medial border of the VMO is identified and, by means of blunt dissection, detached from the intermuscular septum for approximately 10 cm proximally to the adductor tubercle. This process poses no risk to the descending genicular artery and the saphenous nerve. Hofmann advised against using this approach in obese individuals weighing over 90 kg, especially if they also have a short femur or patella alta, on account of the difficulties that, in these conditions, may be encountered in displacing the extensor mechanism. The procedure is also relatively contraindicated in subjects requiring revision surgery and in the presence of a stiff knee with a less than 50° range of motion *(Hofmann, 1991).* Most surgical operations can be performed well with the subvastus approach, and some studies suggest that compared to conventional exposure, the subvastus approach is associated with less preoperative blood loss, less postoperative pain and faster recovery of quadriceps strength (*Cila, 2002*). Potential drawbacks may include less good visibility, the formation of a postoperative hematoma below the VMO, excessive stretching of the fibers of the VMO during displacement of the patella and difficulty increasing the exposure in situations in which this is necessary. The midvastus approach was first described by Engh et al., in 1997 as a compromise between the conventional medial parapatellar (MP) and the subvastus approaches *(Engh, 1997; Sanna, 2013).* The advent of navigation enabled the creation of the mini-midvastus approach (MIS): Straight skin incision over the medial third of the patella from 2 cm proximal to the patella, and then proceeding distally up to the level of the tibial tuberosity. In the next deeper layer, the incision is continued around the medial border of the patella and distally to the level of the tibial tuberosity. The patella is displaced laterally but is not everted in flexion. Knee flexion and extension is necessary to move the soft-tissue surgical window for proximal or distal exposure. Hyperflexion of the knee is necessary only for insertion of the tibial component (*Flören, 2008*).

Based on the available data, the minimally invasive midvastus approach, which spares quadriceps femoris muscle, is a reasonable alternative to the standard medial parapatellar approach, and it results in lesser damage to the quads therefore rehabilitation may be quicker after the implantation of a prosthesis (*Craig, 2008; Wu, 2018)* (Figure 1 and 2).

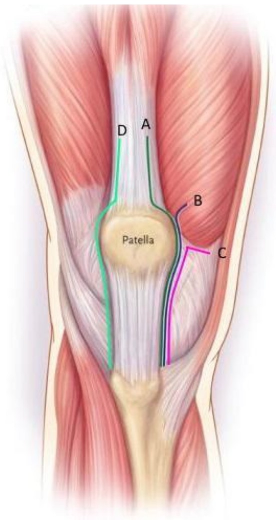

Figure 1.

Exposure of the knee: A: Medial parapatellar, B: Midvastus C: Quad-sparing, D: Lateral parapatellar *(Photo: M. Karadsheh)*

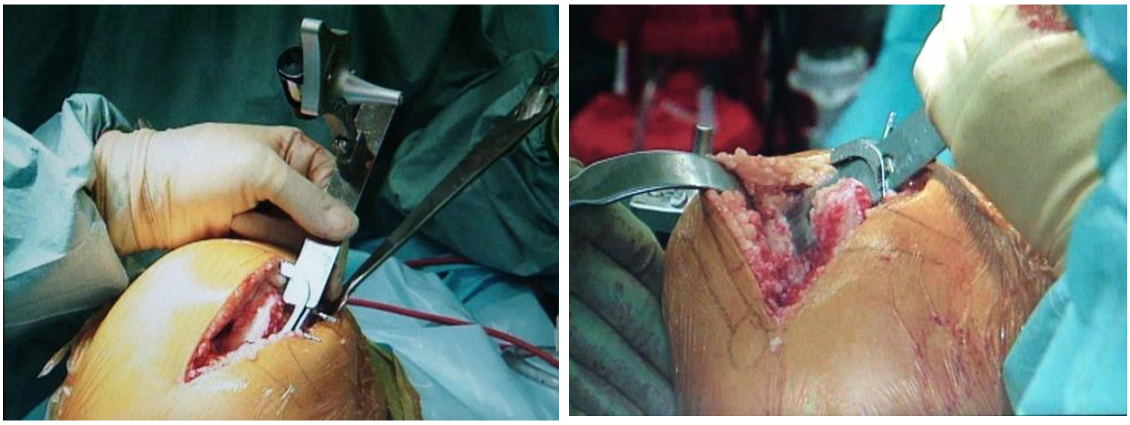

Figure 2.

Minimal invasive midvastus exposure supported by navigation system *(Photo: Bejek)*

According to other authors' multicentre trials, the MIS approach offers no advantage and it is even associated with longer surgical time and greater blood loss. However, MIS-TKR in combination with computer navigation is safe in terms of implant axis and positioning *(Alcelik 2016; Feczkó, 2016).*

In total knee arthroplasty (TKR), the Quadriceps-sparing (QS) approach is considered the most minimised exposure. Soft-tissue preparation starts only at the upper tip of the patella and ends at the tibial tuberosity. After opening of the joint, the patella is dislocated laterally without everting it. Exposure of the articular surface is ensured by the use of a so-called "mobile window" method. QS calls for the use of special instruments *(Wohlrab, 2009)*. The applicability of the approach is disputed since some authors' post-test results suggest that when compared to the conventional medial parapatellar approach (MP), after the surgical operation a higher proportion of prosthetic components may be affected by axial malalignment and component malposition (*Yuan, 2017*), and it does not offer any particular advantage over the mini-midvastus approach.

Evaluating the navigation method in terms of the insertion of prosthetic components, it can be established that the deviation from the optimal position decreases significantly and almost never occurs any component insertion that deviates from the acceptable axial alignment (*Chaucan, 2004; Stöckl, 2004; Seon, 2006; Hetaimish, 2012; Confalonieri, 2019).*

Long term survival of the prosthesis, regardless of the material and shape of the prosthesis, depends on the precise positioning. Sometimes this is not easy to achieve (e.g. due to severe varus-valgus misalignment or significant obesity). Suboptimal joint axis adjustment and the poor position of the components may lead to uneven load, soft tissue imbalance, later on to increased generation of abnormal wear products, early loosening of the prosthesis and forced prosthesis revision *(Bejek, 2007).*

2.2.3 Methods

2.2.3.1. Ultrasound-based motion analysis during stepping

The spatial coordinates of certain anatomical points during stepping were measured by a ZEBRIS CMS10 (Zebris, Isny, Germany) ultrasound-based motion analysis system on a PosturoMed© plate (Haider-Bioswing, Weiden, Germany) *(Boeer, 2010 ab; Kiss, 2011; Müller, 2004)*. A PosturoMed© (Haider-Bioswing GmbH, Weiden, Germany) device is widespread and routinely used in the practice of neurology, sportmedicine and orthopaedic rehabilitation because dynamic stability can be developed with stepping on a moving platform *(Müller, 2004).* This has a rigid platform (12 kg, 60 cm × 60 cm) connected to a rigid frame by eight 15 cm steel springs of identical strength (Figure 3*).* The size and the design of the plate permit the measurement of kinematical parameters of stepping on a fixed and a released (non-fixed, moving) platform, respectively (Figure 3) (*Kiss, 2009).*

Figure 3

Investigated anatomical points: a) Tibial tuberosity to test knee motion b) Anterior superior iliac spine and acromion scapulae in the shoulder girdle to test the motion of the upper body *(Photo: Kiss)*

The movement of the rigid plate was regulated by eight springs permitting the plate to move freely in the horizontal plane. The plate can be fixed with a fastening unit, so the stepping can be examined with a motionless rigid ground as well (Figure 3). Before the measurement, ultrasound-based single markers were attached to record the motion of the designated anatomical points. The measuring head was positioned in front of the individual to be examined (Figures 3 and 4).

Figure 4

Investigated anatomical points: a. Tibial tuberosity to test knee motion b. Anterior superior iliac spine and acromion scapulae in the shoulder girdle to test the motion of the upper body *(Photo: Kiss)*

The WinPosture (Zebris, Isny, Germany) measurement control software calculated the spatial coordinates of the anatomical points from the propagation time of the ultrasound signals as recorded by the measurement system. The measurement frequency was 100 Hz. The intraobserver variation of the spatial position of anatomical points was less than one millimetre; their inter-observer variation was less than 1.5 mm. More details about the measuring method are summarised in the literature *(Kiss, 2009)*.

Our aim was to perform the examinations using the simplest and cheapest devices and to prepare and execute them as fast as possible, considering the limited patience of the mostly elderly subjects with painful knee and limited range of motion. Further expectations were the standardisation and attaining reproducibility. Therefore, the locations of the active, single markers on the body had to be selected to exclude the possibility of displacement during measurement; the anatomical points had to be properly determinable and palpable through the skin. The active markers were fixed in place, using two-sided plaster tape, to the tibial tuberosity (Figure 4) in order to test the motion of the knee and to the anterior superior iliac spine in the pelvis and scapular acromion in the shoulder girdle to test the motion of the trunk (Figure 4). These anatomical points are particularly adequate because there is relatively little motion of the skin over these osseous anatomical points during gait and other types of motion.

First the motion of the knee joint was measured both on fixed and non-fixed plate for 20 stepping cycles each. In the second part the motion of the trunk (motion of shoulder and pelvis) was measured.

2.2.3.3 The measurement of clinical parameters during stepping

From the three directional *(x, y, z)* spatial coordinates of the given anatomical points the following clinical parameters could be calculated:

- motion of the knee joint
- trunk-pelvis motion (rotation and tilting)
- shoulder motion (rotation and tilting)

It is worth performing the measurements not only on fixed but also on non-fixed plate, because the patients' balance control is very important during the early postoperative period *(Kiss, 200; Pethes, 2010).*

Calculated parameters

For each subject in all gait cycles the values the cadence were calculated from the vertical movement of knee, while the motion of the knee joint *(r)* was calculated from three-directional *(x,y,z)* spatial coordinates of the tibial tuberosity (Equation 1, Figure 4) *(Kiss, 2009, 2010; Pethes, 2014).*

$$r = \sqrt{x^2 + y^2 + z^2}$$

Equation 1

From the trunk motion test (motion of pelvis and shoulder) the tilting and rotation of pelvis and shoulder could be calculated using the spatial coordinates of the anatomical points of the anterior superior iliac spine and scapular acromion (Figure 4) *(Kiss, 2009, 2010; Pethes, 2014).*

The obtained data were analysed using multi-variable ANOVA method, supplemented, if necessary, by a Tukey post-hoc test. As regards the controls, variables included laterality (dominant and non-dominant) and gender (male or female). In the patient group, variables included laterality (non-affected and affected), gender (male and female), testing time (preoperatively, and six and 12 weeks postoperatively) and type of operation technique (conventional and minimally invasive technique). Data were processed by SPSS 14 software (SPSS, Chicago, IL USA). Significance levels *(p)* were set at 0.05 in each case ($p \le 0.05$). *(Kiss, 2007; Pethes, 2008, 2014)*

2.2.3.4 Examination of the variability of stepping

The knee motion parameter *(r)* and the angular parameters (rotation and tilting of the shoulder and pelvis) changed constantly over time. After breaking down the parameters into cycles, the maximum and minimum values of the parameter can be defined for each cycle. If it is known for all gait cycles, then the mean, standard deviation and relative standard deviation of a given parameter for a given person can also be calculated from the variable defined for that person. The relative standard deviation thus calculated characterises the variability of the maximum and minimum values of a given characteristic, which is the joint angle, rather than that of the particular joint motion. To avoid this, for the spatial movement of the knee joint as well as for the tilting and rotation of the pelvis and shoulder girdle, all gait cycles of all subjects examined were normalised to 0-100% of cycles. For each subject, angular variables were calculated as all integer percent of the gait cycle. In the next step, for all gait cycles of the individual subject, the mean [*Mean (i)*] and standard deviation [*SD (i)*] were calculated from the characteristic determined at the i-th whole gait cycle percent. Calculation of the mean coefficient value *(MeanCV)* characterising the variability of the total joint motion is presented in equation 2 *(Pethes, 2014).*

$$MeanCV(\%) = \frac{\sum_{i=1}^{10e} \frac{SD(i)}{Mean(i)}}{100} \times 100 \quad i \in \{0 - 100\% \; gait \; cycle\}$$

Equation 2.

Where: *i* represents {0–100% of the gait cycle} thus the mean coefficient of variation *(MeanCV)* represents the mean of all relative standard deviations determined in integer percent.

Statistical analysis

We had the relative standard deviation of the gait frequency for each subject tested as well as value of the mean coefficient of variation *(MeanCV)* pertaining to the spatial motion of the knee joint as well as to the tilting and rotation of the pelvis and shoulder girdle. For the groups of subjects (healthy elderly people; patients operated on with conventional surgical technique and minimally invasive technique), the mean and standard deviation were calculated from the values of the parameters (determined as above) that characterise the variability of the subjects' stepping.

The data obtained were analysed using the bivariate ANOVA method, while for the purpose of the necessary post-hoc testing the Tukey method was used. The laterality of the lower limb (dominant and non-dominant) was used as the variable for the healthy group, while for the patient group the time of testing (preoperative, 6 and 12 weeks after surgery) and laterality (affected and non-affected) were used as variables. Data were processed with the SPSS 14 software (SPSS, Chicago, IL USA). Deviation is deemed significant if $p \leq 0.05$. *(Kiss, 2007; Pethes, 2011).*

2.2.3.5 Measurement of dynamic stability using a sudden perturbation

The measurements of balancing ability in response to sudden unidirectional perturbation were also performed in the Biomechanical Lab at the Orthopaedic Clinic of Semmelweis University, Budapest, Hungary. The plate of the PosturoMed© (Haider-Bioswing GmbH, Weiden, Germany) device could be suspended by releasing the fastening unit, so it provides an instable platform for walking. The springs allow the rigid plate to move freely in the horizontal plane. Planar movement of the suspended rigid plate (bi-directional shift and rotation) can be regulated by the number of springs (4, 6 or 8). During our present test, the movement of the suspended rigid plate of the PosturoMed© therapeutic device was regulated by four springs. In this set up, balancing for the subject was relatively easy, since the direction of the shift of the rigid plate in the horizontal plane coincided with the direction of the displacement. Under these conditions, the test can be safely conducted even within a couple of days immediately after a knee replacement surgery. After the spring-suspended rigid plate is displaced from its middle position, the plate can be fixed again with the help of a fixing-releasing unit belonging to the device (Figure 5)

Figure 5

Measurement arrangement of the provocation test, where the motion of the plate is detected by ultrasound ZEBRIS CMS-10 measurement system (ZEBRIS, Medizintechnik GmbH, Germany) using single markers fastened to the measuring plate *(Photo: Kiss 2010)*

Once the fixing device is released, the rigid plate intends to return to its original position, which models the sudden change of direction (*Müller, 2004; Boeer, 2010; Kiss, 2011b*). When there is no person standing on the rigid plate, the rigid plate performs undamped free oscillation (the damping effect of the internal friction can be ignored). The person standing on the plate set in motion loses their balance; this person can regain their balance by damping the moving plate. In this case, the rigid plate performs damped free oscillation and damping characterises the balancing ability of the subject. During the balancing process after the sudden change in direction, an arbitrary number of anatomical points could be recorded with an ultrasound-based motion analysis system. Preliminary tests have shown that in each test, the movements of the person tested are completely unique. In view of this, it makes sense to turn the question around: to what extent can the person tested dampen the movement of the oscillating plate, i.e. what damping coefficient does the balancing ability of the person tested represent? The aspect which makes raising this question also possible is that no displacement of any kind is allowed between the rigid plate and the foot, i.e. the contact is “ideal”. If this question is raised, the movement of the rigid plate has to be recorded by a ZEBRIS CMS10 (Zebris Medizintechnik GmbH, Germany) ultrasound-based measuring system equipped with individual specific markers attached to the side of the rigid plate. The measuring methods were detailed by Kiss *(Kiss, 2011b).*

Calculated characteristics

In characterising dynamic balancing, the question was how the subject can damp the motion of the rigid plate set into oscillation by their balancing; therefore it is expedient to characterise the balancing ability exhibited after an abrupt change of direction with one oscillation parameter of the damped oscillation. Based on the differential equations 3. and 4. of the damped free oscillation, best suited for this is Lehr's damping ratio which is the ratio of the actual to the critical damping; its magnitude is equal to the total constant of the springs (*c*), at the total mass of the subject and that of the rigid plate (*m*), which are known and dependent on the actual damping (*k*).

$$\Lambda = \frac{1}{i} \ln \ln \frac{K_0}{K_i}$$

Equation 3

where K_0 is the amplitude at time $t = t_0$;

K_i is the amplitude at time $t = t_i$; where *i* refers to the signal oscillation number (e.g. *i*=2, 3, 4,…,n for the 2nd, 3rd,… n-th oscillation)

Since the damping of the system corresponds to the balancing ability of the subject, the Lehr's damping number (D) is a suitable for characterising the balancing ability.

$$D\,[\%] = \frac{\Lambda}{\sqrt{\Lambda^2 + 4\pi^2}} * 100$$

Equation 4.

where $\pi = 3.14$;

Λ is the logarithmic decrement

The value of Lehr's damping ratio can be between 0 and 1. If $D = 0$, there is no damping, undamped oscillation develops and the subject loses their balance. If $D = 1$, damping is equal to the critical damping, no oscillation occurs, and the balancing ability is ideal. The higher the Lehr's damping ratio is, the better the actual damping is, i.e. the better the subject's balancing ability will be. In the discipline of science dealing with oscillations, the Lehr's damping number used for the characterisation of damped free oscillation is also suitable for characterising the balancing ability after an abrupt change of direction *(Kiss, 2011a,b).* It can be deduced from the solution of the differential equations 3 and 4 of the damped free oscillation that that Lehr's damping ratio can be determined from the movement of the rigid plate *(Kiscelli, 1997).*

Statistical analysis

The Lehr's damping ratio was expressed as the mean and standard deviation. The uniformity of the standard deviations was assessed by the F-test. Differences between the groups were determined by two-sample t-test, while the difference between the two sides was analysed with one-sample, paired t-test. The obtained data were evaluated using a multi-variable ANOVA method. Significance levels were set at $p \leq 0.05$. *(Pethes, 2015).*

3. RESULTS

3.1. Kinematic parameters characterising knee motion during stepping

For better clarity, the kinematic parameters are summarised in two tables (Tables 1 and 2).

In the case of unilateral knee arthrosis, compared to persons of similar age and the healthy other knee, the range of knee motion decreases on both the fixed and moving platform (Tables 1 and 2). The motion range of the “healthy side” also fails to reach the motion range of the age-matched control group, but the difference is not significant $(p>0.09)$. Two weeks after surgery, compared to the preoperative value, the motion range of both knees decreases, so this tendency, independently of the exposure method, applies to the non-operated (relatively healthy) side as well. However, in the case of minimally invasive surgical exposure, the difference is significant only on the non-operated side, while in the case of conventional exposure, it is significant on the operated side as well ($(p<0.04)$. At two weeks after surgery, in the case of conventional exposure, the motion of the knee in vertical direction (z-axis) is significantly smaller compared to both the preoperative status and the knee operated on with minimally invasive surgical exposure. In the case conventional exposure, the patient compensates for reduced vertical movement with increased lateral (x-direction) movement (Tables 1 and 2).

By the end of the third postoperative month, for both exposure methods, the motion of the knee joint on the operated side still lags behind that of the healthy knee, but this lag is mainly due to reduced back and forth (y-direction) motion. For the minimally invasive exposure, there is significant improvement experienced on both types of the plate, compared to the preoperative values ($p_{fix}<0.03$, $p_m<0.04$). In contrast, in the case of conventional exposure, the rate of improvement is significant only on the moving plate, compared to the preoperative values ($p_f<0.007$ *és* $p_m<0.03$) (Tables 1 and 2).

Table 1. Kinematic parameters of stepping on fixed plates

Parameters		Group I. (Healthy)	Group III. (Mini exposure) operated side			
Time		Non dominant	Preoperative	Postoperative w. 2	Postoperative w. 6	Postoperative w. 12
Knee motion	x	16.72±11,07	29.21±25.46	18.25±11.43	21.98±14.01	15.53±13.39
	y	210.1±53.33	115.13±52.49*†	106.03±71.42*	155.6±39.55*†	153.06±34.4*‡
	z	40.86±34.25	28.97±23.95	30.98±42.65	47.88±47.27†	38.47±29.5
	$\sqrt{x^2+y^2+z^2}$	216.34±58.08	124.99±56.74*†	114.66±79.47*	167.31±52.32†	160.19±40.56*‡
Parameters		Group I. (Healthy)	Group II. (Conventional exposure) operated side			
	x	16.72±11.07	16.55±12.58	25.02±17.23	10.19±7.10†	16.62±11.01
	y	210.1±53.33	122.6±76.28*	108.28±50.20*	116.28±63.02*	144.53±65.30*
	z	40.86±34.25	31.22±26.99	11.68±11.50	27.77±19.27	31.78±32.95
	$\sqrt{x^2+y^2+z^2}$	216.34±58.08	130.3±76.93*	112.92±51.15*†	121.21±63.71*	150.28±70.81*
Parameters		Group I. (Healthy)	Group III. (Mini exposure) non- operated side			
Time		Dominant	Preoperative	Postoperative w. 2	Postoperative w. 6	Postoperative w. 12
	x	18.66±20.27	26.14±19.18	23.78±18.66	35.3±20.37	12.41±12.95‡
	y	204.72±42.6	151.75±79.87	104.28±26.06‡	194.58±59.09	166.25±61.25
	z	37.86±34.54	25.58±21.05	30.07±21.7	57.16±49.88	32.86±19.05
	$\sqrt{x^2+y^2+z^2}$	211.95±45.45	157.94±80.86	113.08±31.07*‡	209.16±67.67	171.04±62.01
Parameters		Group I. (Healthy)	Group II. (Conventional exposure) non- operated side			
	x	18.66±20.27	18.77±16.79	15.9±20.17	24.22±16.11	21.18±22.73
	y	204.72±42.6	132.93±60.19*	125.08±38.35*	123.13±61.09*	149.42±76.09
	z	37.86±34.54	31.8±23.47	32.08±33.66	21.63±24.94	35.7±40.06
	$\sqrt{x^2+y^2+z^2}$	211.95±45.45	139.3±63.54*	132.22±48.09*	129.52±63.10*	157.58±83.92

Marking of significance: * compared with Gr I (healthy control), † compared with the other side, ‡ compared with the preoperative values

Table 2. Kinematic parameters of stepping on non-fixed plates

Parameters		Group I. (Healthy)	Group III. (Mini exposure) operated side			
Time		Non dominant	Preoperative	Postoperative w. 2	Postoperative w. 6	Postoperative w. 12
Knee motion	x	16.23±9.67	27.27±14.5	38.54±24.5	24.55±1481	14.45±13.47‡
	y	195.32±51.03	104.08±40.91*†	78.47±50.0*	133.48±60.11	123.24±35.22*†‡
	z	36.64±29.96	28.48±22.17	20.97±15.82	34.85±44.05	28.98±24.72
	$\sqrt{x^2+y^2+z^2}$	200.96±53.91	113.88±41.39*†	95.1±47.20*	143.56±67.84	129.77±36.8
Parameters		Group I. (Healthy)	Group II. (Conventional exposure) operated side			
	x	16.23±9.67	25.55±12.10	13.6±8.41‡	15.53±9.51	23.37±10.77
	y	195.32±51.03	110.71±63.99*	90.14±29.37*†	110.16±52.48*	125.28±52.18*‡
	z	36.64±29.96	25.62±23.93	18.62±25.87†‡	36.42±46.8	22.73±24.49
	$\sqrt{x^2+y^2+z^2}$	200.96±53.91	119.19±64.04*	94.82±34.42*†‡	117.06±41.54	131.63±52.91*‡
Parameters		Group I. (Healthy)	Group III. (Mini exposure) non-operated side			
Time		Non dominant	Preoperative	Postoperative w. 2	Postoperative w. 6	Postoperative w. 12
	x	20.64±15.06	23.63±14.2	25.88±17.46	26.01±17.02	12.77±10.5
	y	197.63±57.2	139.93±63.78	96.42±27.23*	166.4±68.12	140,42±60.4*
	z	32.95±30.99	22.15±20.05	20.71±12.83	45.77±34.29‡	34.28±27.95
	$\sqrt{x^2+y^2+z^2}$	203.51±59.43	144.18±65.59	103.08±30.76*	176.5±72.61	146.38±64.19
Parameters		Group I. (Healthy)	Group II. (Conventional exposure) operated side			
	x	20.64±15.06	18.92±19.69	7.28±5.8	21.68±20.43	22.91±21.14
	y	197.63±57.2	117.36±56.06*	126.14±39.42*	106.2±59.12*	130.85±59.2*
	z	32.95±30.99	32.16±20.37	30.26±23.7	30.63±28.45	22.49±24.02
	$\sqrt{x^2+y^2+z^2}$	203.51±59.43	126.8±54.12*	130.86±42.95	114.74±64.61*	136.58±62.97*

Marking of significance: * compared with Gr I (healthy control), † compared with the other side, ‡ compared with the preoperative values

Tilt of the pelvic girdle in patients suffering from knee osteoarthritis (Tables 3 and 4) is significantly increased (due to compensatory motion of the relatively intact hip joint) compared to the values of the healthy age-matched control group (*$p<0.007$*). For minimally invasive exposure, by the end of postoperative month 12, the rate of tilt significantly decreases compared to the preoperative value (*$p<0.03$*), but it is still considered significantly increased compared to the healthy control group (*$p<0.05$*) (Tables 3 and 4).

Table 3. Kinematic parameters of stepping on fixed plates

Parameters	Healthy	Mini exposure			
Time		Preop	Postop w. 2	Postop w. 6	Postop. w. 12
Tilting of shoulder	1.58±1.22	6.01±5.45	5.1±3.28	5.12±2.97	2.11±1.36‡
Rotation of shoulder	7.29±3.04	5.35±2.16	6.48±3.16	6±3.64	5.82±3.69
Tilting of pelvis	2.64±2.31	9.45±6.01	8.92±2.22*	7.64±2.76*‡	5.1±1.50*‡
Rotation of pelvis	3.61±2.21	4.78±2.41	5.14±3.45	3.44±1.85	3.58±2.96
	Healthy	Conventional exposure			
Tilting of shoulder	1.58±1.22	4±3.8	8.6±9.26	3.71±2.78*	2.31±2.71
Rotation of shoulder	7.29±3.04	4.9±2.63	3.47±1.99*	4.52±2.73*	6.5±2.65
Tilting of pelvis	2.64±2.31	6.34±3.67*	8.85±3.07*	5.33±3.51	4.75±2.62
Rotation of pelvis	3.61±2.21	3.54±2.53	3.47±3.62	4.25±3.33	4.99±2.82

Marking of significance: * compared with healthy control, ‡ compared with the preoperative values

Table 4. Kinematic parameters of stepping on non-fixed plates

Parameters	Healthy	Mini exposure			
Time		Preoperatív	Postoperative week 2	Postoperative week 6	Postoperative week 12
Tilting of shoulder	1.19±1.0	6.5±5.29*	5.32±4.96	4.8±3.55	1.4±2.02‡
Rotation of shoulder	7.84±3.13	4.38±2.71*	7.32±2.48	7.04±4.0	5.28±1.95
Tilting of pelvis	2.17±2.35	8.82±4.87*	8.96±2.37*	7.7±2.69*	3.55±0.80‡
Rotation of pelvis	4.35±1.78	5.84±4.09	7.18±1.73*	3.84±1.87	3.66±2.52
	Healthy	Conventional exposure			
Tilting of shoulder	1.19±1.0	3.08±2.82	3.35±3.08	3.36±3.86	1.64±1.81
Rotation of shoulder	7.84±3.13	5.44±3.52	5.45±4.12	4.51±3.14*	5.27±2.41
Tilting of pelvis	2.17±2.35	6.3±2.99*	6.52±1.40*	5.11±3.91	4.18±2.83‡
Rotation of pelvis	4.35±1.78	4.57±2.84	1.85±2.63	3.37±2.64	3.9±2.23

Marking of significance: * compared with healthy control, ‡ compared with the preoperative values

As in the pelvis, shoulder girdle tilt is increased in patients with knee arthrosis, but the rate of tilt is significantly reduced only for minimally invasive exposure by the end of postoperative week 12 compared to the preoperative value ($p<0.008$), however, it still remains elevated compared to healthy controls (Tables 3 and 4).

3.2. Examination of the regularity of gait during stepping

The healthy persons without exclusion criteria involved into the trial and TKR recipients were able to do stepping on both the fixed and non-fixed rigid plate, the latter one requiring greater balancing ability. For this reason, no patient was excluded from the trial. The results are summarised in Table 5.

Regularity of stepping was first tested on a fixed plate. The knee OA significantly affected the regularity of the parameters characterising stepping. The coefficient of variation (*CV*) of step frequency increased significantly ($p<0.001$) (Table 5).

The mean coefficient of variation (*Mean CV*) of the spatial motion of the affected side knee joint to be operated on decreased significantly ($p<0.0008$) (Table 5), while the mean coefficient of variation of the motion of the knee on the unaffected, healthy side and that of the shoulder girdle and pelvic girdle significantly increased compared to the values of the healthy control group ($p<0,001$) (Table 5, Figure 6).

Table 5. The mean ± standard deviation of cadence and mean CV of knee motion, tilting and rotation of pelvis and shoulder

Parameters		**Fixed plate**							**Non-fixed plate**						
		Control	**Group II.**			**Group III.**			**Control**	**Group II.**			**Group III.**		
			preop	*postop week 6*	*postop week 12*	*preop*	*postop week 6*	*postop week 12*		*preop*	*postop week 6*	*postop week 12*	*preop*	*postop week 6*	*postop week 12*
Cadence		8.7 ±0.9	23.8 ±1.7 *	16.4 ±1.2 *,†	12.4 ±1.1 *,†	24.3 ±1.6 *	15.1 ±1.3 *,†,◊	10.7 ±1.1 *,†,◊	11.3 ±0.9 ‡	29.3 ±1.9 *,‡	18.7 ±1.5 *,†,‡	15.8 ±1.3 *,†,‡	30.1 ±2.0 *,‡	17.1 1.6 *,†,,‡◊	13.2 ±1.3 *,†,‡,◊
Knee motion	nd	6.9 ±0.7	2.8 ±0.2 *	3.5 ±0.3 *,†	4.6 ±0.4 *,†	2.9 ±0.2 *	4.1 ±0.3 *,†,◊	5.7 ±0.5 *,†,◊	8.2 ±0.8 ‡	2.9 ±0.3 *	3.7 ±0.3 *,†	5.1 ±0.4 *,†	3.0 ±0.3 *	4.3 ±0.4 *,†,◊	6.2 ±0.5 *,†,◊
	d	6.8 ±0.6	32.7 ±3.0 *,#	27.7 ±2.8 *,†,#	22.4 ±2.2 *,†,#	31.4 ±2.9 *	23.8 ±2.5 *,†,#,◊	17.1 ±2.0 *,†,#,◊	8.1 ±0.7 ‡	39.3 ±3.6 *,#,‡	33.9 ±2.9 *,†,#,‡	26.4 ±2.4 *,†,#,‡	38.1 ±3.4 *,#,‡	29.9 ±2.5 *,†,#,‡,◊	25.1 ±2.1 *,†,#,‡
Pelvis girdle	tilting	21.8 ±1.8	41.4 ±3.9 *	35.6 ±3.3 *,†	30.8 ±2.7 *,†	42.4 ±4.1 *	30.8 ±2.8 *,†,◊	27.6 ±2.6 *,†,◊	27.9 ±2.1 ‡	46.5 ±4.1 *,‡	40.1 ±3.9 *,†,‡	35.5 ±3.3 *,†,‡	47.8 ±4.2 *,‡	37.2 ±3.6 *,†,‡	32.3 ±3.0 *,†,‡
	rotation	23.7 ±2.0	45.7 ±4.3 *	39.3 ±4.0 *,†	31.6 ±3.6 *,†	46.6 ±4.6 *	33.3 ±3.9 *,†,◊	25.9 ±3.1 *,†	29.1 ±2.5 ‡	49.3 ±4.1 *	43.8 ±4.3 *,†	33.2 ±4.1 *,†	49.8 ±4.4 *	39.9 ±4.1 *,†	32.4 ±3.3 *,†
Shoulder girdle	tilting	13.2 ±1.5	29.4 ±2.5 *	23.5 ±2.0 *,†	19.9 ±1.8 *,†	27.9 ±2.4 *	20.3 ±1.7 *,†,◊	13.9 ±1.5 †,◊	17.0 ±1.8 ‡	33.4 ±2.2 *,‡	27.3 ±2.7 *,†,‡	24.6 ±2.6 *,†,‡	31.9 ±2.1 *,‡	25.8 ±2.0 *,†	18.2 ±1.9 †,‡,◊
	rotation	17.1 ±1.9	35.7 ±3.1 *	30.4, ±3.3 *,†	25.7 ±3.1 *,†	34.8 ±3.2 *	26.7 ±2.9 *,†,◊	19.8 ±2.3 *,†,◊	26.4 ±2.3 ‡	39.1 ±3.5 *,‡	34.9 ±3.4 *,†	31.4 ±3.2 *,†,‡	37.8 ±3.6	34.8 ±3.5 *,†,‡	29.7 ±3.1 *,†,‡

Remarks: Group I: control group, Group II: patients operated upon by conventional technique, Group III: patients operated upon by minimally invasive technique; preop: before operation; postop: after operation; *preop* data measured preoperatively, *postop* data measured postoperatively, *nd* non-dominant leg in healthy control subjects and affected leg in patients, *d* dominant leg in healthy subjects and non-affected leg in patients; * Significant difference compared to healthy control subjects; † Significant difference compared to preoperative patient value; # ^{d}Significant difference comparing the healthy (contralateral) side to the affected side; ‡ Significant difference between fixed and non-fixed plate; ◊Significant difference between the patient groups (Group II vs Group III)

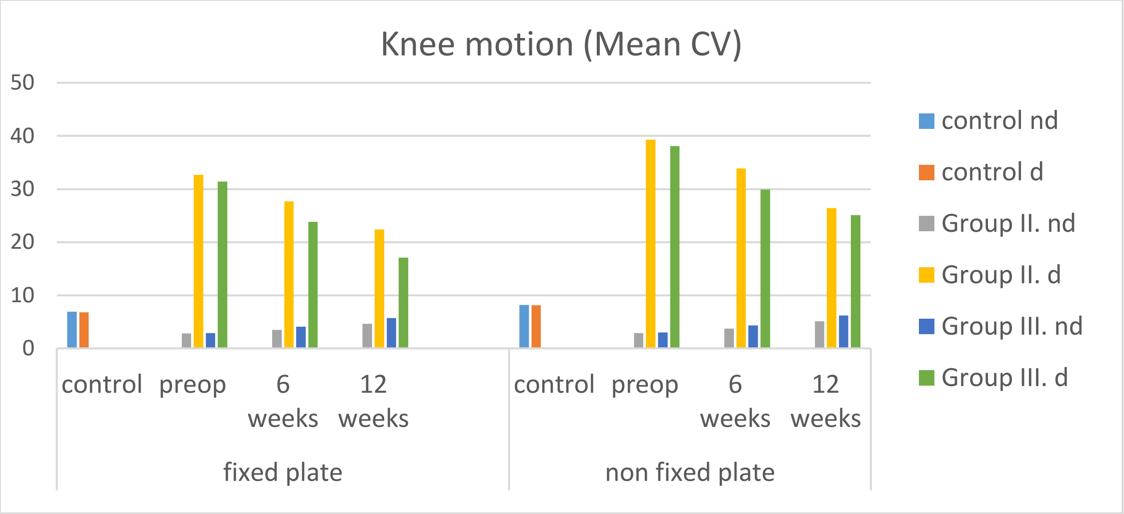

Figure 6

The mean CV of knee motion, tilting and rotation of pelvis and shoulder

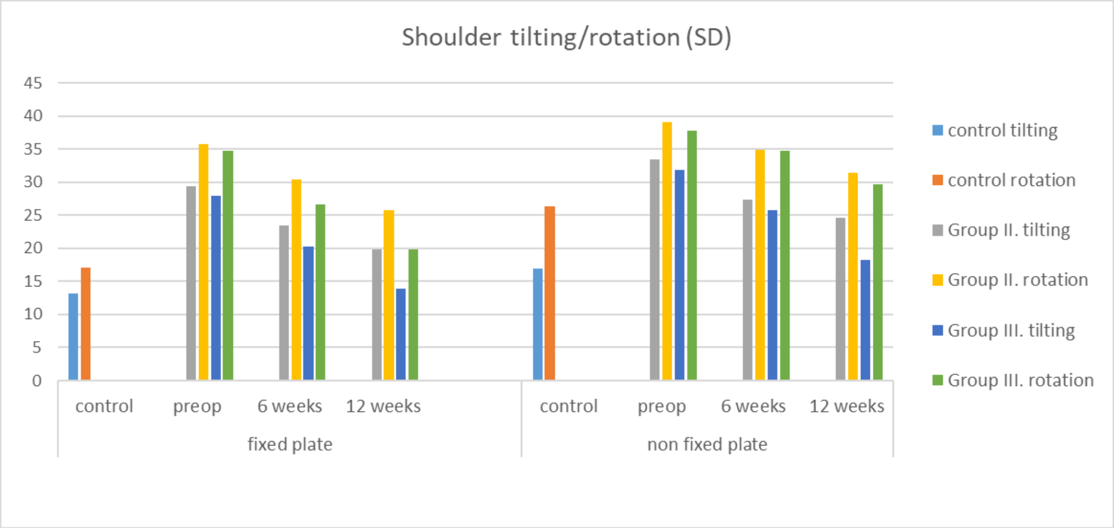

Figure 7

The mean CV of tilting and rotation of shoulder

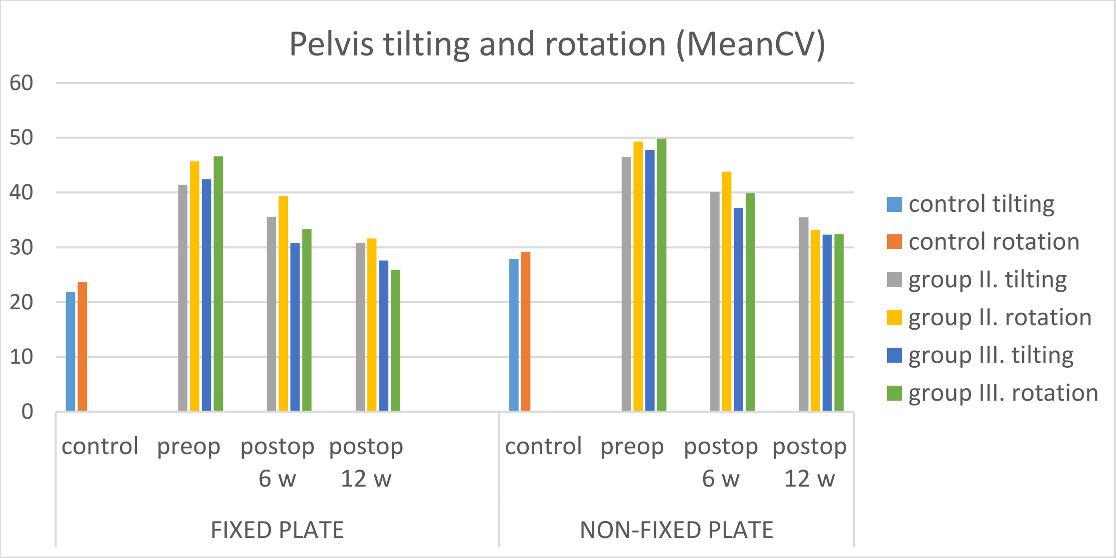

Figure 8

The mean CV of tilting and rotation of pelvis

In the early postoperative stage, the values of coefficient of variation (*CV*) for step frequency of stepping showed a steady improvement compared to preoperative values, while the mean coefficient of variation (*Mean CV*) for the spatial motion of the knee joint on the healthy, unaffected side and that for the motion of the shoulder girdle and pelvic girdle significantly decreased *($p<0.03$)*. As early as postoperative week 6, the mean coefficient of variation (*Mean CV*) for the spatial motion of the knee joint on the affected side significantly increased compared to preoperative values *($p<0.03$)*. However, even at 12 weeks after surgery, they were still significantly lower ($p<0.04$) than the values of the healthy control group of similar age. When comparing the mean coefficient of variation of the spatial motion of the affected and unaffected knee joints, a significant difference is obtained both before and after surgery *($p<0.01$)* (Table 5, Figure 6). At 6 and 12 weeks after surgery, the patients in Groups II and III were significantly different in terms of all measured parameters, except for pelvis rotation tested at 12 weeks after surgery *($p<0.09$)* (Table 5, Figure 8).The values of coefficient of variation (*CV*) for the gait parameters of the patients operated on with minimally invasive technique come closer to the normal values more rapidly than the values of the patients operated on with conventional technique.

Regularity of stepping was tested on non-fixed plate as well (Table 5). Comparison to the values of the healthy control group shows that the knee OA *($p<0.02$)* and the implantation of a knee prosthesis significantly *($p<0.006$)* affected gait regularity (Table

5., Figure 7). Both before and after surgery, the trend of change in regularity was consistent with the trend determined during stepping on the fixed plate. The mode of exposure significantly influenced the regularity of all parameters characterizing stepping on the non-fixed plate throughout the early postoperative stage. In the early postoperative period, the regularity of the parameters tested in Group III nears the average of the healthy control group more quickly than the values of Group II, but does not reach them even at week 12. When comparing the mean CVs of Group II and Group III, the difference is significant throughout, with the exception of the values for contralateral side motion ($p>0.07$), the pelvic rotation ($p>0.06$) and tilt ($p>0.08$) and shoulder rotation ($p>0.06$) at 12 weeks after surgery (Table 5, Figure 6).

3.4. Results of the ultrasound-based provocation (abrupt change of direction) test

Lehr’s damping number *(D)* describing the dynamic balancing ability is influenced by the sex and age of the subjects *(Kiss, 2011),* in view of this, the evaluation is broken down by sex. All subjects managed to perform the test, so there was no exclusion for this reason. In the ultrasound-based abrupt direction change (provocation) test (Lehr’s damping number [D] mean ±standard deviation), the dominant limb of healthy controls is compared with the relative healthy limb not undergoing surgery, while the non-dominant limb is compared with the operated limb affected by OA. The results are summarised in Table 6 (Figure 9).

Table 6. Change in Lehr’s damping ratios [D, %] during provocation (abrupt direction change) test within the first 3 month after surgery

Groups	**Sex**		**Standing**		
			on two legs	dominant/ non affected leg	non-dominant/ affected leg
Healthy(Gr I.)	*Men*		0.465 ± 0.033	0.447 ± 0.030	0.290 ± 0.039 ^{a,b}
	Women		0.499 ± 0.029 ^{g}	0.483 ± 0.028 ^{g}	0.341 ± 0.031 ^{a,b,g}
Group II.	*Men*	prior to op	0.325 ± 0.049 ^{c}	0.305 ± 0.042 ^{c}	0.084 ± 0.049 ^{a,b,c}
		6 weeks	0.321 ± 0.034 ^{c}	0.317 ± 0.039 ^{c}	0.105 ± 0.039 $^{a,b, c}$
		12 weeks	0.362 ±0.037 ^{c,d,e}	0.357 ±0.035 ^{c,d,e}	0.187 ±0.035 ^{a,b,c,d,e}
	Women	prior to op	0.320 ± 0.041 ^{c}	0.312 ± 0.049 ^{c}	0.088 ± 0.047 ^{a,b,c}
		6 weeks	0.308 ± 0.037 ^{c}	0.304 ± 0.037 ^{c}	0.108 ±0.033 ^{a,b,c,d}
		12 weeks	0.367 ±0.035 ^{c,d,e}	0.360 ±0.037 $^{c,d, e}$	0.191 ±0.033 ^{a,b,c,d,e}
Group III.	*Men*	prior to op	0.328 ± 0.049 ^{c}	0.311 ± 0.042 ^{c}	0.085 ± 0.041 ^{a,b,c}
		6 weeks	0.375± 0.031 ^{c,d,f}	0.358± 0.035 ^{c,d,f}	0.157± 0.037 ^{a,b,c,d,f}
		12 weeks	0.414± 0.037 ^{c,d,e,f}	0.402± 0.031 ^{c,d,e,f}	0.209± 0.035 $^{a,b,c,d, e,f}$
	Women	prior to op	0.338 ± 0.049 ^{c}	0.324 ± 0.049 ^{c}	0.099 ± 0.047 ^{a,b,c}
		6 weeks	0.341 ± 0.035 ^{c,d,f}	0.379 ± 0.032 ^{c,d,f}	0.159 ± 0.038 ^{a,b,c,d,f}
		12 weeks	0.409 ± 0.035 ^{c,d,e,f}	0.399 ± 0.037 ^{c,d,e,f}	0.217 ± 0.034 ^{a,b,c,d,e,f}

[a] Significant difference in D values between upon one leg and two legs measured values

[b] Significant difference in D values between non-dominant/affected leg and the dominant/non-affected leg
[c] Significant difference in D values between OA patients and healthy control group
[d] Significant difference in D values between preop and postop values
[e] Significant difference in 6 weeks and 12 weeks after operation
[f] Significant difference in D values between the two operation techniques (conventional-mini exposure)
[g] Significant difference in D values between the genders

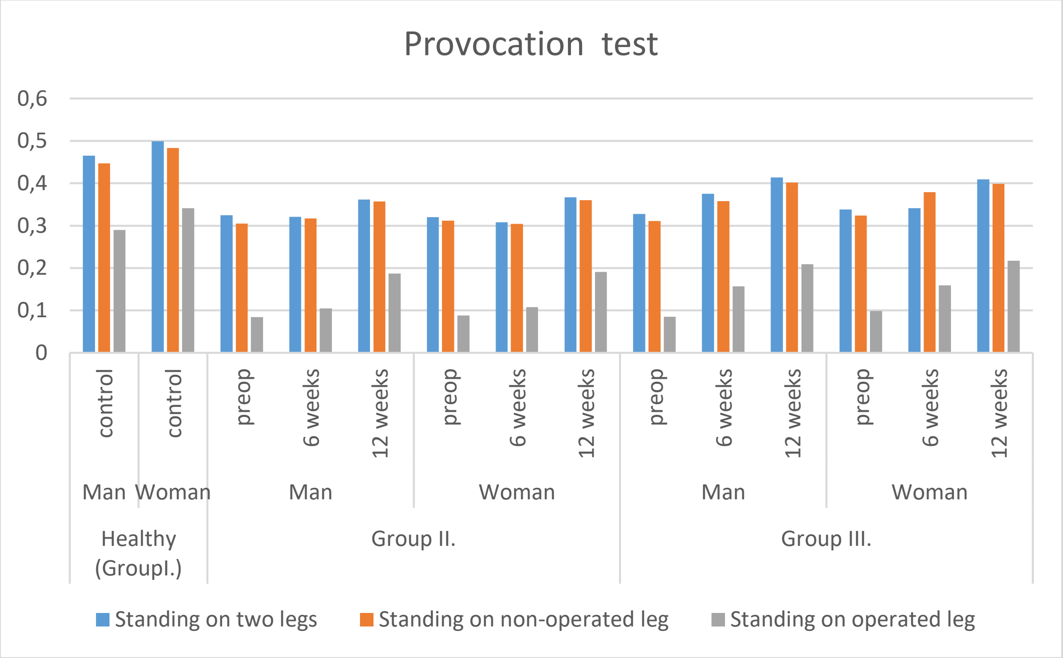

Figure 9
Results of provocation test conducted preoperatively and at 6 and 12 weeks postoperatively compared to age-matched control group

For both patient groups, the Lehr's damping number, calculated from the measured values during week 6 after surgery was not significantly different from the preoperative values ($p>0.14$). The Lehr's damping number increases gradually from the 6th week postoperatively, and is significantly higher at the postoperative 12th week than the preoperative values ($p<0.008$). Nevertheless, the values at week 12 after surgery were still significantly lower than those of the controls ($p<0.01$) (Table 6., Figure 9).

For patients operated on with minimally invasive technique, the Lehr's damping number calculated from the results of the measurement taken at weeks 6 and 12 postoperatively is significantly higher ($p_{week\ 6}<0.03$, $p_{week\ 12}<0.0007$) than the preoperative values, but still significantly lower than those of the control group (Gr.I.) ($p<0.01$) *(Pethes, 2015)*. For patients operated on with minimally invasive technique (Gr. III.), the Lehr's damping ratios calculated from the results of measurements taken at weeks 6 and 12 postoperatively is significantly higher than the values of the group of patients operated on with the conventional technique (Gr. II.) ($p<0.03$) (Table 6, Figure 9).

4. DISCUSSION

4.1. Effect of exposure method of knee arthroplasty on kinematic parameters characterising knee motion

We aimed to determine how the knee arthroplasty conducted with different exposures affects the clinical parameters characterising knee motion during stepping. The method used for testing the motion of the knee joint as well as that of the related joints is reliable and reproducible. The gait amplitudes in anteroposterior direction of the group of healthy subjects used as age-matched controls without musculoskeletal disorders are significantly higher compared to the tested patients with knee osteoarthritis. This is consistent with previous research findings *(Hinman, 2002).*

In the early postoperative period, the tested kinematic parameters of the motion of the healthy knee joint on the non-operated side return to the pre-operative level by the end of the 3rd month. In the case of minimally invasive exposure, the motion range of the affected knee joint is significantly greater than the preoperative values and the range of vertical motion reaches the values of the healthy side already in the postoperative 6th week (Table 1 and 2). The same cannot be said for conventional exposure. The range of motion of the knee joint operated on with conventional exposure is reduced in comparison to the contralateral healthy knee, mainly due to the decrease of motion in the anteroposterior direction.

In the case of both exposures, the increased neuromuscular control on the moving plate, which requires more balancing, resulted in reduced motion of the operated knee joint compared to the healthy contralateral side. This is due to a reduction in back and forth motion. It can be established that neuromuscular protection, pain reduction and safety-seeking gait (walking in a safe manner) reduce the greatest motion of range, which is the back and forth motion.

Increasing the tilt of the pelvic and shoulder girdles compensates for reduced knee joint motion. The rotation of the pelvic and shoulder girdles does not take part in the compensation, which partly contradicts our previous results (*Bejek, 2006*). This is explained by the fact that we studied stepping and rotation plays a role mainly in translatory motion. The kinematic parameters examining the knee motion seem to confirm that in the case of operations performed with navigation from smaller exposure there is a faster improvement trend in stepping after surgery than after conventional surgery with full exposure.

4.2. Effect of exposure method of knee arthroplasty on stepping regularity

The second objective of our study was to establish how knee arthroplasty performed with different exposures affects the regularity of gait. The regularity of the stride-to-stride movement of the lower extremities is characterized by variability parameters (relative standard deviations) describing the regularity of length and temporal parameters of gait (*Newell, 1993; Fuchs, 1994; Hausdorff, 2005; Dubost, 2006*). If the variation in the length and temporal parameters of gait results in a reduced value, then the subject's lower extremity is performing a similar movement from stride to stride, with each step occurring in a similar way with minimal variation (*Hausdorff, 2001; Heiderscheit, 2000*). Mean coefficient of variation (*Mean CV*), which describes the regularity of joint motion, is a variability parameter that reflects the adaptability of joints (*Hausdorff, 2005; Heiderscheit, 2000*). Lower extremity movement is described by knee motion, upper body movement is defined by pelvis and shoulder tilt and rotation, while variability is characterised by their relative standard deviation.

The knee motions characterising the spatial motion of the knee as well as the pelvic and shoulder tilt and rotation are angular parameters that are characterised by the mean coefficient of variation (*Mean CV*) (*Hausdorff, 2005; Smith 2006; McClealland, 2009*). A higher mean coefficient of variation (Mean CV) of the spatial motion of knee joint indicates better joint flexibility, which ensures continuous step-by-step correction, alignment and coordination of the motions of individual joints and body parts, thus ensuring a coordinated, rhythmic gait pattern (*Fuchs, 1994; Beuchet, 2007*). A decrease in the regularity of angular parameters induced an increase in the variability of temporal parameters, which in conjunction led to deterioration in the complexity (*Smith, 2006; Gergoulis, 2007*) and stability (*England, 2006; Hausdorff, 2005*) of the motion.

The gait is harmonious if the variability of the spatial and temporal parameters characterising the regularity of the gait pattern is small, but the mean standard deviation of the angular parameters characterising the flexibility of the joint is high. (*Maki, 1997; Hausdorff, 2001; Brach, 2005; Beauchet, 2007; Kiss, 2010 a,b*).

The increased relative standard deviation in the cadence of the operated patients (Groups II and III) in the pre- and postoperative periods shows a deterioration in limb motion regularity compared to Group I used as control, which correlates with previous literature *(Newell, 1993; Dubost, 2016)*. The irregularity may also be due to increased pain, which may be indicated by low scores of the quality of life tests. The results obtained are similar to those measured on a treadmill 6 months after knee arthroplasty *(Kiss, 2012).* In the pre-operative and early post-operative period, the *Mean CV* of the affected knee decreased compared to the age-matched control group of healthy subjects. In the postoperative period, the mean coefficient of variation *(Mean CV)* of the motion of the affected knee increased significantly, but still did not reach the values of the control group at 12 weeks after TKA. This suggests that the joint is stiffer (*Smith, 2006; Kiss, 2010*), which is influenced by the pain caused by arthrosis in the preoperative period. In the postoperative period, stiffness may develop due to pain, reduced muscle strength and proprioceptive deficits (*Hubley-Kozey, 2006*). Based on the results obtained, it can be stated that both before surgery and at the postoperative week 12, an increase in the coefficient of variation of cadence and a decrease in the mean coefficient of variation (Mean CV) of the affected knee motion led to decreased coordination and increased variability of motions *(Newell, 1993; Hausdorff, 2005; Dubost, 2006; Smith, 2006).* These data indicate an increased risk of falls. The increased mean CV of the non-affected knee motion as well as the pelvis and shoulder motions show that these joints also play an important role in the compensatory mechanisms that ensure gáti stability. This confirms the previous statements made by our team *(Bejek, 2011; Kiss, 2011a; Kiss, 2012*).

Prior to surgery, no significant difference was detected between the parameters of groups II and III, which confirms the random selection conditions. In the early postoperative period, a significant difference was found between groups II and III in all the parameters studied. The values of the patients operated on with navigation-assisted minimally invasive technique (group III) improved faster than the values of the patients operated on with the conventional method (group II), but the standard deviation of the gait and the mean coefficient of variation (Mean CV) of the affected knee joint motion were still significantly different from the control group even at 12 weeks after surgery.

When gait testing was performed on an unstable, non-fixed plate, the mean coefficient of variation (Mean CV) of the non-affected knee motion as well as the values of the pelvic and shoulder tilts were greater than those measured on a fixed plate. This may suggest that contralateral knee motions as well as shoulder and pelvic tilts may play an important role in compensation and maintaining stability. These deductions correlate with the results of previous measurements on treadmill *(Kiss, 2011a; 2012)*.

4.3. Effect of knee arthroplasty performed with different exposure methods on the dynamic balancing ability of the knee

In the further part of our studies, we investigated the deterioration of balancing ability after a sudden change of direction, which is closely associated with an increased risk of tragic falls in the elderly, in the preoperative period and the early period after TKA. The values obtained were compared with those of the age-matched control group. The question arose as to whether the method of TKR exposure influenced the faster convergence of the response to the sudden change of direction compared to the control. After TKR performed with conventional technique, the Lehr's damping ratio at week 6, determined by all three test methods, was not significantly different from the preoperative values (Table 6, Figure 9), and was significantly lower than the values in the control group. Previous studies have described that in the early period after TKR surgery, static balancing ability measured during double limb standing is worse than that of healthy people *(Gauchard, 2010).* The results of our own researches have also demonstrated that in the early postoperative period after TKR surgery, the values of the provocation test conducted during standing on the operated side and on the unaffected contralateral side do not improve significantly compared to the preoperative period, i.e. the risk of falling is very high throughout the early postoperative period *(Nevitt, 1989; Pethes, 2012).* In the next stage of the postoperative period, the Lehr's damping number characterising the balancing ability increases steadily for all the three test methods (Table 6, Figure 9), but does not reach the values of the control group for any of the test methods at week 12 postoperatively. This high risk of falling may be due to the fact that the non-operated side is not yet able to compensate for the reduced balancing capacity of the operated side (*Nevitt, 1989; Pethes, 2012*). The presumed reason for this is that the muscles are not yet able to take over the role that the affected joint capsule and the removed ligaments play in balancing (*Freeman, 1965*), or the joint capsule and the damaged muscles have not yet regenerated properly and movement provokes pain. The Lehr’s damping number calculated from the values recorded during standing on the unaffected side and standing on both limbs also decreased compared to the values of the control group, which is in line with Gage's *(Gage, 2007)* finding suggesting that kinematic responses in unilateral diseases and in the case of surgeries are bilateral. In patients undergoing minimally invasive knee arthroplasty, the Lehr's damping number characterising the dynamic balancing gradually improves over the entire postoperative period compared to preoperative values, and the improvement is faster than that in patients undergoing conventional surgery, but does not reach the values of the control group in any of the test methods at week 12 postoperatively *(Pethes, 2012).*

The presumed reason for the difference between the two exposure methods is that the minimally invasive technique entails much less joint capsule involvement than the conventional technique. In both groups of patients, the sex of the subject did not affect the ability to balance after an abrupt change of direction (Table 6, Figure 9), i.e. the physiological difference between the sexes disappears *(Pethes, 2012).* In addition to increasing joint motion and muscle development, rehabilitation protocols should also focus on developing dynamic balancing ability. It should be taken into consideration that at week 12 postoperatively, the dynamic balancing ability is worse for both exposure methods than for the control group, which indicates that the risk of falling is high. In other words, the ability to adapt to unexpected situations, e.g. walking on uneven or slippery ground, is still significantly lower in the early postoperative period compared to the age-matched control group, so prolonged physiotherapy and the use of walking aids should be considered at postoperative follow-up examinations to prevent accidents, after assessing the effect of age and comorbidities *(Pethes, 2012).*

5. CONCLUSIONS

Knee joint endoprosthesis implantation is one of the most frequently used orthopaedic procedures. However, 20 percent of the patients who underwent the operation are dissatisfied with the outcomes *(Confalonieri, 2019).* The reason for this is not clear, but a mechanical alignment beyond 3° of varus-valgus can represent the most important cause of failure of TKR and consequently patient dissatisfaction. Neutral mechanical alignment is the main goal in every TKR *(Confalonieri, 2019).* This can be achieved through different tools, such as extramedullary and intramedullary guides, patient-specific instrumentation (PSI) and computer-assisted surgery (CAS). The use of an intramedullary guide may lead to fat embolism, there is an increased risk of fatty embolism and it is impossible to use in cases of bone deformity and post-traumatic deformities (sequelae of trauma). Regarding the extramedullary guide, it becomes more difficult to use in cases of great obesity or increased soft-tissue volume around the tibia. Meta-analysis suggests that surgeries conducted with PSI fail to improve the mechanical axis and implant survivorship *(Confalonieri, 2019).* Computer-assisted total knee arthroplasty has provided a useful tool in assisting the surgeon to achieve more accurate mechanical axis through precise bone cuts and ligament balancing. Early follow-up after CAS showed a more accurate mechanical axis and better functional outcomes, and two meta-analyses demonstrated a definitely better mechanical axis and longer implant survival *(Moskal, 2014; Rebal, 2014; Confalonieri, 2019).* Besides the better mechanical axis of the components, the quality of life parameters are also better compared to the traditional surgical method, but the operative time is longer and thus the use of tourniquet also lasts longer.

The main objective of the research conducted with biomechanical methods and summarized so far was to determine how the knee joint prosthesis implanted with different surgical techniques (conventional and navigation-assisted minimally invasive approaches) affects kinematic parameters characterising the knee motion, gait regularity and dynamic balancing ability of the knee joint in the event of an abrupt change of direction.

For safe, harmonious walking, it is essential that motion is performed within the correct range and with adequate accuracy, and that the person always regains balance in the event of a sudden stumble or fall. Based on the statistical processing of the results of the motion studies carried out, the following new scientific findings can be concluded:

Thesis 1: The kinematic parameters (range of motion of the knee joint, range of motion of the pelvic girdle rotation, range of motion of the pelvic girdle tilt, range of motion of the shoulder girdle rotation, and range of motion of the shoulder girdle tilt) that characterize stepping were significantly influenced by the method of exposure of the total knee arthroplasty on fixed plates (Tables 1. and 3.). The anteroposterior gait amplitudes of the healthy subjects used as age-matched controls without musculoskeletal disorders were significantly higher compared to the patients with knee osteoarthritis (Tables 1. and 3.). In the early post-operative period, the kinematic parameters of the motion of the knee-joint of the non-operated side, i.e. those characterising the motion of the relatively healthy knee joint, are back to the pre-operative level by the end of the 3rd month. With minimally invasive exposure, the motion range of the affected knee joint is significantly greater than the preoperative values and the vertical range of motion reaches the values of the healthy side already in the postoperative 6th week. In the case of conventional exposure, this cannot be said even at the end of 12th week. Increasing the tilt of the pelvic and shoulder girdles compensates for the reduced knee joint motion. The explanation for the differences between the two methods could be that the surgical damage of the adjaecent tissues around the joint in case of minimal invasive exposure is much less.

Thesis 2: The above mentioned observations are valid on non-fixed, moving plates as well. There are no significant alterations compared with the results measured on fixed plate (Tables 2. and 4.). It may prove that different circumstances influence the motion range of the knee much less than the different methods of the exposure.

Thesis 3: The increased coefficient of variation of the cadence observed pre- and postoperatively in patients operated on by different methods (navigated minimally invasive and conventional methods) shows that the regularity of limb movements deteriorates compared to the age-matched healthy controls without musculoskeletal disorders (Table 5, Fig 6-8). The results obtained suggest that both before surgery and at postoperative week 12, an increase in the variation of cadence of the affected knee motions led to decreased coordination of motions and increased variability of motions (Table 5, Fig 6-8). In the early postoperative period, the values of CV for the patients operated on with navigation-assisted minimally invasive technique (group III) decreased significantly faster than those for the patients operated on with the conventional method (group II), but the coefficient of variation characterising gait regularity and the mean coefficient of variation (*Mean CV*) of the affected knee joint motion were still significantly different from the control group even at week 12 postoperatively.

Thesis 4.: The above mentioned observations are valid on moving non-fixed plates as well. There are no significant alterations compared with the results measured on fixed plate (Table 5., Fig. 6-8.). The explanation could be that the different circumstances influence the regularity of cadence much less than the different methods of the exposure. When gait testing was performed on an unstable, non-fixed plate, the mean coefficient of variation (*Mean CV*) of the non-affected knee joint motion as well as the pelvic and shoulder tilt values were greater than those measured on a fixed plate. This may suggest that contralateral knee motions as well as shoulder and pelvic tilt may play an important role in compensation and maintaining stability.

Thesis 5.: In the early period after total knee arthroplasty (3 months), the response to sudden change of direction during standing, i.e. the provocation test values on both extremities, on the operated side and on the non-affected contralateral side, do not improve significantly compared to the preoperative status, i.e. the risk of falling is very high throughout the early period after surgery. The Lehr's damping number increases steadily, but does not reach the values of the control group at week 12 after surgery (Table 6, Figure 9). The Lehr’s damping number calculated from the values measured during standing on the unaffected side and on both limbs also decreased compared to the values of control group, which is in line with Gage's *(Gage, 2007)* finding: kinematic responses in unilateral diseases and surgery manifest bilaterally. The presumed reason for the difference between the two exposure methods is that the minimally invasive technique causes much less surgical damage to the joint capsule than the conventional technique. The other reason is that in medial parapatellar exposure, the vastus medialis muscle adhering to the patella and part of the rectus femoris muscle radiating into the quadriceps tendon are also virtually detached from the patella, as a result, not only the muscle function but also the proprioception is impaired in the early immediate postoperative period until the muscle heals. In addition to increasing joint motion and muscle development, rehabilitation protocols should also focus on developing dynamic balancing skills.

A summary of my results: I have found that the exposure method of TKR significantly influenced the kinematic parameters characterising stepping and the two factors characterising safe gait: gait regularity and dynamic balancing ability (response to abrupt change of direction). By the 3rd month of the postoperative period, the values of the patients operated on with minimally invasive exposure combined with navigation were closer to those of the control group than the values of the patients operated on with conventional exposure, but they failed to reach the values of the control group. Due to my research I can formulate the next statements:

1. The kinematic parameters (range of motion of the knee joint, range of motion of the pelvic girdle rotation, range of motion of the pelvic girdle tilt, range of motion of the shoulder girdle rotation, and range of motion of the shoulder girdle tilt) that characterize stepping were significantly influenced by the method of exposure of the total knee arthroplasty on fixed plates.
2. With minimally invasive exposure, the motion range of the affected knee joint is significantly greater than the preoperative values and the vertical range of motion reaches the values of the healthy side already in the postoperative 6th week. In the case of conventional exposure, this cannot be said even at the end of postoperative 12th week.
3. Different circumstances (fixed or non-fixed plates) influence the motion range of the knee much less than the different methods of the exposure.
4. An increase in the variation of cadence and the decreased knee motion of the affected knee led to decreased coordination of motions and increased variability of motions preoperatively and still at the postoperative week 12
5. In the early postoperative period the coefficient of variation characterising gait regularity for the patients operated on with navigation-assisted minimally invasive technique (group III) decreased significantly faster than those for the patients operated on with the conventional method (group II).
6. The coefficient of variation and the mean coefficient of variation (*Mean CV*) of the affected knee joint motion were still significantly different from the control group even at week 12 postoperatively.

7. The mean coefficient of variation (*Mean CV*) of the non-affected knee joint motion as well as the pelvic and shoulder tilt values were greater than those measured on a fixed plate. This may suggest that contralateral knee motions as well as shoulder and pelvic tilt may play an important role in compensation and maintaining stability.

8. In the early period after total knee arthroplasty (3 months), the response to sudden change of direction during standing, i.e. the provocation test values on both extremities, on the operated side and on the non-affected contralateral side, do not improve significantly compared to the preoperative status.

9. The Lehr’s damping number calculated from the values measured during standing on the unaffected side and on both limbs also decreased compared to the values of control group, which indicates that kinematic responses in unilateral diseases and surgery manifest bilaterally.

6. SUMMARY

As knee osteoarthritis (OA) worsens, the kinematic parameters of knee joint motions, gait stability and gait safety deteriorate, as evidenced by the deterioration of dynamic balancing ability and gait regularity. With advancing age, in 3-5% of the population, the degree of degenerative deviation justifies the implantation of a knee prosthesis, which can ensure the safety and stability of gait in the long term. The different exposure methods significantly affect gait parameters in the early postoperative period. In our research, we investigated to what extent TKR with different exposure methods (navigation-assisted minimally invasive and conventional) affects the quality of life and functional tests, the kinematic parameters of knee joint motions, the gait regularity and the dynamic balancing ability measured by ultrasound-based abrupt change of direction test during the first three months of the postoperative period. Our results demonstrate that in the patients involved in the study, the exposure method of knee arthroplasty significantly influences the kinematic parameters of knee motions, gait regularity, and dynamic balancing ability. In the postoperative 3rd month, the results of the research show that the surgical method of knee arthroplasty should be taken into account when postoperative rehabilitation is being planned. Exercises to improve dynamic balancing and proprioceptive development of the non-operated side are also recommended. The difference between surgical methods should also be taken into account in determining when to discontinue the use of medical aids and equipment prescribed in the postoperative period.

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