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Title: Toe grip strength training improves gait performance and prevents falls in patients after total knee arthroplasty

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Abstract

Falls after total knee arthroplasty are common in knee osteoarthritis patients due to advanced age and implant-induced sensory function changes. We reported the influence of toe grip strength on falls in knee osteoarthritis patients. This study aimed to determine whether toe grip strength training after total knee arthroplasty is related to the screening assessment and incidence of falls. Elderly patients undergoing unilateral total knee arthroplasty were divided into toe grip strength training group and control group. Six types of training were conducted on bilateral toes. The primary outcomes were changes in toe grip strength and timed up and go test time from preintervention to 12 weeks post-intervention. Secondary outcomes involved several factors, including the occurrence of falls. The analysis included 37 participants in both groups. Toe grip strength training group had a shorter timed up and go test and stronger bilateral toe grip strength than control groups. The changes of timed up and go test time was significantly correlated with the changes of toe grip strength on the affected side. There were significantly fewer falls in toe grip strength training group than in control group between 3 and 12 months after total knee arthroplasty. toe grip strength training was useful in improving walking ability and preventing falls in postoperative total knee arthroplasty patients. The advantage of toe grip strength training is that it is an unoperated muscle function, so the intervention can be conducted safely without specialist supervision unless the toes are impaired.

Key words: Toe grip strength training; Timed up and go test; Falls; Total knee arthroplasty

足趾把持力トレーニングは人工膝関節全置換術後患者の歩行能力を改善し転倒を予防する

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人工膝関節全置換術後の転倒は、高齢であり関節インプラントによる固有感覚機能の変化のため頻繁にみられる。我々は、変形性膝関節症患者の転倒に対する足趾把持力の影響を報告した。本研究は、人工膝関節全置換術後の足趾把持力トレーニングの効果が、スクリーニング評価および転倒の発生率と関連するかどうかを明らかにすることを目的とした。片側人工膝関節全置換術を受けた高齢患者を、足趾把持力トレーニング群と対照群にわけた。両側の足趾に対して 6 種類のトレーニングが実施された。主要アウトカムは、介入前から介入後 12 週までの足趾の握力と timed up and go test の計測時間の変化量とした。副次的アウトカムは、転倒の発生を含む複数の要因とした。解析対象は両群共に 37 名であった。足趾把持力トレーニング群では、対照群に比べ、timed up and go test の計測時間が短く、両側の足趾把持力が強かった。timed up and go test の計測時間の変化量は、患側の足趾握力の変化量と有意な相

関関係を認めた。人工膝関節全置換術後 3 ヶ月から 12 ヶ月の間に、足趾把持力トレーニング群では対照群に比べて転倒が有意に少なかった。足趾把持力トレーニングは、人工膝関節全置換術後患者の歩行能力向上と転倒予防に有用であることが判明した。足趾把持力トレーニングの利点は、人工膝関節全置換術の非手術部位であるため、足趾に障害がない限り専門家の監督なしに介入を安全に実施できることである。

Introduction

Total knee arthroplasty (TKA) is an effective treatment to reduce knee joint pain and improve activities of daily living. However, according to previous reports, 17–38% of TKA patients experience falls within 1 year after TKA[1-3]. The reason is that TKA is a surgery mainly undertaken for the elderly and, associated with altered sensory and motor functions of the knee, which may impair balance control when standing and walking[4]. Although the general elderly population also has a fall incidence of around 30%[5], the falls after TKA can lead to severe fractures, such as peri-implant fractures, and hinder the restoration of quality of life[6]. The Timed up and go test (TUG), an assessment of combined movements such as standing, sitting and walking, has been reported to be predictive of falls and is often used as a screening tool for falls in clinical settings[7]. In postoperative TKA patients, who are often treated at an advanced age, the TUG is effective in the clinical assessment of balance function and postoperative outcomes.

Toe grip strength (TGS) has recently gained interest, as previous reports have shown that TGS affects falls in patients with knee osteoarthritis (KOA)[8]. Tsuyuguchi et al.[9] reported that nursing home residents who received TGS training showed significant improvements in TGS and fall risk scores. Kojima et al.[10] also reported that toe-grip exercises could improve TGS and balance ability of home-based rehabilitation users. TGS training improves balance ability and fall risk and is therefore expected to improve TUG, which is used as a screening assessment for falls. For TGS is associated with TUG in healthy elderly patients[11], TGS training can contribute to improved TUG times in postoperative TKA patients, many of whom are treated at an older age. An advantage of TGS training for postoperative TKA patients is that it can be performed without pain in the surgical area since it involves a non-surgical muscle function. Another advantage of TGS training is that it is safe for postoperative patients to perform at home, as it can be performed in a sitting position.

However, we were unable to find any previous reports on how the presence or absence of TGS training relates to physical ability and fall incidence in patients after TKA. Our hypothesis was that TGS training started after TKA would improve TGS and contribute to shorter TUG times and reduced fall rates. Whether TGS training for postoperative TKA patients is useful for improving physical ability and reducing the risk of accidents that may occur after TKA needs to be clarified. The aim of our study was to evaluate how TGS training is related to physical ability and fall incidence by dividing postoperative TKA patients into a TGS training group (T-group) and a control group (C-group) in a non-randomized way.

Methods

Study design and participants

This was a nonrandomized controlled study with 2 parallel groups. Participants were recruited from a single hospital in Japan, and elderly patients who underwent unilateral TKA between May 2020 and December 2021 due to a diagnosis of KOA were included. The inclusion criteria were as follows: 1) individuals who underwent unilateral TKA due to a diagnosis of KOA; 2) individuals between 60 and 84 years of age; 3) individuals who had the ability to ambulate independently or with a T-shaped cane before and 3 months and 1 year after TKA; 4) individuals who were able to complete a physical therapy assessment and questionnaire; and 5) individuals who provided informed consent to participate in the study. The exclusion criteria were as follows: 1) individuals who were diagnosed with rheumatoid arthritis, idiopathic osteonecrosis, neurological diseases, other musculoskeletal diseases or foot and ankle disorders; 2) individuals with toe flexion problems by hallux valgus, floating toe and nail deformities that could significantly impair basic movements, such as walking; 3) individuals with severe depression or dementia, which would hinder evaluation; and 4) individuals who fell during hospitalization. The participants who met the selection criteria were divided into two groups according to whether they wished to participate in the TGS training program: the T-group (the group receiving TGS training and usual physiotherapy) and the C-group (the group receiving usual physiotherapy only).

Ethical issues

This study complied with the Declaration of Helsinki and was approved by the Research Ethics Committee of Kashiba Asahigaoka Hospital (ID: 2020-04-21-007) and the registered University Hospital Medical Information Network Clinical Trials Registry (ID: UMIN000048550). Details of the study protocol and aim were explained to all participants, both verbally and in writing. All study participants signed an informed consent form prior to participating in the study.

Interventions for T-group participants

TGS training in the T-group began the day after discharge from the hospital, lasted 12 weeks and was conducted in the participant's home. Six types of training were conducted on bilateral toes based on previous studies (Fig. 1)[9]. The participant and examiner determined the feasibility of the six types of training during hospitalization. Then, participants were asked to exclude items that were difficult to implement and to implement the remaining items. For safety reasons, all interventions were performed in a seated position in a chair. Participants were instructed to record "done" in the designated training notebook when they completed the TGS training using the default items and the frequency (Fig. 2). The therapist checked the training notebook for outpatient physical therapy once or twice per week. Participants were asked to conduct the program a minimum of four times per week. As common home exercises, both groups were instructed to perform range of motion (ROM) knee flexion and knee extension strength exercises. The quantity and frequency of common home exercises were individually determined by the therapist in charge, depending on the participant's degree of improvement and home environment.

Study procedure

The study protocol is shown in Fig. 3. Preoperative outcomes were assessed on the day before TKA. Outcome measurements were evaluated in the rehabilitation room by the therapist in charge. Outcome assessments were performed preoperatively and 12 weeks postoperatively by the same therapist. However, the guidance of the intervention in the TGS group was provided by a person independent of the assessors. Whether falls had occurred was determined by the nurse on the day before TKA and at 12 weeks and 1 year after TKA. All patients started physical therapy the day after TKA, which consisted of ROM exercises for the affected knee and gait practice with a walker. No TGS training was provided during inpatient physical therapy.

The surgical technique for TKA and the choice of implant were selected by two orthopaedic surgeons based on the suitability of the patient. The component was cemented, and the incision was made with a para-patellar approach. All participants had the patella replaced. Physical therapy during hospitalization was provided six days per week (excluding Sunday).

Primary outcomes

The primary outcomes were changes (Δ) in TGS and the TUG time from preintervention to 12 weeks post-intervention. A toe grip dynamometer (T.K.K.3362; Takei Scientific Instruments, Niigata, Japan) was used to measure TGS (Fig. 4) in a seated position with the hip and knee joints flexed at 90° and the ankle in a neutral position. The examiner adjusted the position of each participant's heel stopper so that at least the first to third toes could grasp the grip bar of the device and secured the foot with the provided immobilization belt to prevent it from moving. After practicing several times, the TGS of both sides was measured at maximum force for approximately three seconds. TGS was measured twice, and the mean value (kg) was calculated. Measurements were taken for both sides. The TGS has excellent intrarater reliability, with an intraclass correlation coefficient (ICC) of 0.92[12].

The TUG[13] test is a walking time test that involves standing up from a chair, walking for 3 m, turning, walking back to the chair, and sitting down. The test was developed as an evaluation of mobility and screening for fall risk. The normal walking speed of the participants was measured due to concerns about falls during the measurement. Two measurements were taken and averaged (second). The TUG has excellent intrarater reliability, with an intraclass correlation coefficient (ICC) of 0.94[14].

Secondary outcomes

Secondary outcomes included background information, the occurrence of falls, pain, isometric knee extension (IKES), the modified Fall Efficacy Scale (mFES) score, and the Knee Injury and Osteoarthritis Outcome Score (KOOS).

Background information, including age, height, weight, body mass index (BMI), and gender, was collected preoperatively; Kellgren-Laurence grading (K-L grade) was performed for both sides by the orthopaedic surgeon using X-ray images. The type of implant (PS or CS), the affected side and the number of hospitalization days were determined using electronic medical records. Walking style was assessed preoperatively and at 12 weeks postoperatively by a therapist.

The occurrence of falls was assessed by asking participants and their family members who lived with them whether they had fallen. The reason that the participants' family members who lived with them were also asked about falls was due to the participants' potential recall bias. A fall was defined as "an event that resulted in a person coming to rest unintentionally on the ground or other lower level, not as a result of a major intrinsic event or overwhelming hazard"[15]. Falls were excluded if they were not related to gait, standing or transfer, for example, a fall from a bicycle or ladder. Assessments were performed 1) on the day of admission prior to TKA, 2) at the 12-week postoperative follow-up visit for falls (from discharge to 12 weeks postoperatively), and 3) at the 1-year postoperative follow-up visit for falls (from 12 weeks to 1 year postoperatively).

Pain levels at rest and during walking were measured using a visual analog scale (VAS) with a 100-mm horizontal line ranging from 0 (no pain) to 100 (worst pain imaginable)[16].

IKES was measured using a handheld dynamometer (μ-tas F1; ANIMA Corp.) with the participant in a seated position with the knee at 90° of flexion[17]. Participants were instructed to gradually increase the intensity of knee extension against the dynamometer for approximately 2 s and maintain their maximal force output for approximately 3 s. Two measurements were taken and averaged (kgf).

Fear of falling was assessed using the Japanese version of the mFES. The mFES consists of 14 items (score range: 0–140 points) that are subjectively evaluated on a scale from 0 to 10 in terms of a person's confidence in their ability to perform daily indoor and outdoor activities without falling[18]. The mFES measures confidence in performing certain movements and actions without falling, with higher scores indicating greater self-efficacy in preventing falls and less fear of falling.

The KOOS consists of 42 factors separated into five subscales: pain (nine factors), symptoms (seven factors), activities of daily living (ADL) function (17 factors), sport and recreation function (five factors), and quality of life (four factors). Each of the five subscale scores is calculated as the sum of the included factors. The scores are converted to a 0–100 scale, with 0 representing extreme knee problems and 100 representing no knee problems, as is common in orthopaedic scales[19]. A Likert scale is used for scoring; all factors have five answer options ranging from 0 (no problems) to 4 (extreme problems), and scores between 0 and 100 represent the percentage of the total possible score achieved. In addition to the analysis and interpretation of the five subscales separately, an aggregate score is calculated.

Statistical analysis

Data were analysed descriptively by calculating means and standard deviations or numbers and percentages. For all analyses, the significance level was set to 5%. All statistical analyses were performed using software (SPSS Inc.; SPSS version 26.0 for Windows). Statistical analyses were carried out by researcher not part of the intervention and evaluation of this study. Changes (Δ) were calculated as differences before and 12 weeks after the intervention[20]. We performed the Shapiro–Wilk test to examine normality.

Comparisons between groups of baseline variables and Δ variables were analysed with an unpaired t test or the Mann–Whitney U test.

Intragroup comparisons before and 12 weeks after TKA in the T-group and C-group were analysed with a paired t test or Wilcoxon's signed rank test.

Comparisons between groups regarding the occurrence of falls (preoperatively, 12 weeks postoperatively, 1 year postoperatively), gender, K-L grade (both sides), type of implant, the affected side, the number of hospitalization days, and walking style (preoperatively, 12 weeks postoperatively) were analysed by the chi-squared test or Fisher's exact test.

To examine variables associated with Δ TUG time in the T-group, Pearson or Spearman correlation coefficients were analysed.

Data availability statement

The datasets generated for this study will be made available upon reasonable request, which should be directed to the corresponding author.

Results

Comparison of baseline characteristics

Figure 5 illustrates the study flowchart, which includes the processes of subject enrolment, allocation, and analysis. Each groups included 37 participants. There were no dropouts in either group. Table 1 shows the baseline characteristics for the T-group and C-group. No significant differences were observed in any factors between the groups.

Compliance rate of the exercise

The compliance rate of 37 participants in the T-group who exercised at least four times a week for 12 weeks was 100%. In short, all participants conducted TGS training at least four times a week for 12 weeks.

Improvement from before to 12 weeks after surgery

Table 2 shows a comparison of the degree of improvement from before to 12 weeks after surgery. The T-group showed improvements in the TUG time, TGS on the affected side, TGS on the unaffected side, walking pain on the affected side, walking pain on the unaffected side, the mFES score, the KOOS Symptoms subscale score, the KOOS Pain subscale score, the KOOS ADL subscale score, and the KOOS QOL subscale score. The C-group showed improvements in the TUG time, resting pain on the affected side, walking pain on the affected side, walking pain on the unaffected side, the mFES score, the KOOS symptoms subscale score, the KOOS Pain subscale score, the KOOS ADL subscale score, and the KOOS QOL subscale score. Both groups showed improvement at 12 weeks postoperatively compared to preoperatively.

Comparison of changes between the T-group and C-group

Comparisons of changes in scores collected at baseline and post-intervention between the two groups are shown in Table 3. The T-group showed significant improvements in ΔTUG time and TGS on the affected sid and on the unaffected side compared with the C-group.

Correlation analyses of ΔTUG time and changes in other factors

The correlations between ΔTUG time and changes in other factors are shown in Table 4. ΔTUG time showed a significant negative correlation with ΔTGS on the affected side.

Comparison of falls and walking style in the T-group and C-group

Table 5 shows a comparison of the occurence of falls at each time point and walking style at 12 weeks postoperatively. The T-group had a significantly lower number of falls than the C-group at one year after TKA.

Discussion

The aim of our study was to evaluate how TGS training was related to physical ability and fall incidence by dividing postoperative TKA patients into a T-group and C-group in a non-randomized way. The T-group completed a training programme related to TGS at least 4 times per week for 12 weeks after discharge home after TKA. The results of our study were consistent with our hypothesis. The T-group had significantly improved TGS and TUG times from before to 12 weeks after surgery and had significantly fewer falls in the 1-year postoperative period compared to the C-group. In the early postoperative period, knee joint function is still recovering, and early intervention such as TGS training would be a useful and safe intervention for postoperative TKA patients. To our knowledge, this study is the first to demonstrate that the implementation of TGS training is associated with improved physical ability and reduced fall incidence among postoperative TKA patients. Falls after TKA can lead to severe fractures, such as peri-implant fractures[6]. No adverse events occurred in either group during the study period. There were no dropouts. This is because TGS training is a nonsurgical and painless procedure.

In the T-group, bilateral TGS at 12 weeks postoperatively improved compared to the preoperative values, and ΔTGS was significantly greater in the T-group than in the C-group. Needless to say, the effect of the training programme was related to receiving TGS training within a certain period of being discharged home. Not only was TGS enhanced by TGS training in the T-group, but significant improvements were also found in the TUG time. Furthermore, the significant negative correlation found between ΔTGS and ΔTUG time in the T-group indicated that the TUG time was improved by the TGS training intervention. This is because no interventions to improve TUG time were carried out other than TGS training in the T-group. The reason why improvement in TGS was associated with an improvement in the TUG time in postoperative TKA patients is that toe flexion in a terminal stance supports the rigid supination of the foot for push-off that is needed for smooth progression of the body during walking[21] Enhanced TGS may have contributed to a faster TUG time, as it enhanced the kicking force and contributed to an increase in walking speed. As toe movement is a product of the interaction of the flexor-extensor muscles that make up the lower part of the foot[22], toe stability providing postural stability while walking may also be the reason for the improvement in the TUG time. We consider that TGS training may have contributed to postural stability during gait changes in movements that require a change in direction, such as the TUG, and reduced the deceleration of speed when changing direction.

We report novel information that the T-group had significantly fewer falls at 12 months postoperatively than the C-group. Since TKA postoperative patients are older and at risk of postoperative complications due to a certain number of falls, the association between fewer postoperative falls and improved TGS is an important finding. The finding that the 12-week postoperative TGS intervention sustained a reduction in falls up to 1 year postoperatively is a very positive result. A valid explanation for the above result may be that the TGS intervention helped participants develop and sustain the TGS exercise routine. As TGS is not a muscle strength that is consciously used on a daily basis, it is possible that the T-group acquired an awareness of exercising TGS as a result of participating in this trial. Another possible reason could be the 100% adherence rate of the T-group to the exercise programme at 12 weeks postoperatively, which is a very enthusiastic group of participants.

The first speculation that TGS training contributes to fall prevention is the prevention of stumbling over steps in the home. As stumbles are caused by the toes catching on steps and other surfaces, a functioning toe joint is thought to prevent stumbling. Especially after TKA surgery, when the knee motion is tight, movement beyond the ankle joint is particularly important. Second, it is thought that balance is maintained by a kinetic chain from the lower part of the foot by stepping on the ground with the toe flexor muscle during changes in plantar pressure, such as changes in direction. Biomechanical research is essential to verify these speculations in the future.

This study had some major limitations. The first limitation is the lack of assessment of foot function other than TGS. Participants who were unable to measure TGS or who were treated by a doctor for their toes were not included, but the hallux valgus and arch angle were not accounted for. It was previously reported that lower toe deformities change the load distribution when walking because such a condition results in the toes being pulled back into extension, thus reducing their contact area[23]. Toe deformities alter weight distribution under the foot when walking[23]. This may also affect the TUG time. Second, previous studies have reported decreased physical activity as well as hip weakness as risk factors for falls[24, 25]. Because we did not evaluate these factors and did not include these results in our analysis, we could not determine the relative contribution of TGS to physical activity and muscle strength for the above factors in older adults with KOA. Thirdly, the sample size is not calculated in a priori. Without sample size calculations, it is unclear whether the intervention study was conducted with sufficient power. Finally, participants were not randomly assigned, which may introduce selection bias into this results. This limitation could affect the generalizability and validity. To improve the quality and rigor, it is essential to acknowledge this potential bias and address it in future research. Therefore, we plan to conduct a randomized controlled trial to verify the effectiveness of TGS training and minimize the impact of selection bias on our conclusions.

The aim of our study was to examine how TGS training was related to physical ability and the occurrence of falls in postoperative TKA patients in a nonrandomized trial, dividing them into a training group and a control group. The results showed that TGS training was useful in improving walking ability and preventing falls in postoperative TKA patients. The advantage of TGS training is that it is an involuntary muscle function, so the intervention can be conducted safely without specialist supervision unless the toes are impaired. We recommend TGS training as a new training method for TKA patients, many of whom are elderly facing the risk of falls.

References

1. Swinkels A and Allain TJ. 2013. Physical performance tests, self-reported outcomes, and accidental falls before and after total knee arthroplasty: an exploratory study. *Physiother Theory Pract* 29: 432-442. doi: 10.3109/09593985.2012.755590.
2. Matsumoto H, Okuno M, Nakamura T, Yamamoto K, Osaki M and Hagino H. 2014. Incidence and risk factors for falling in patients after total knee arthroplasty compared to healthy elderly individuals. *Yonago Acta Med* 57: 137-145.
3. Tsonga T, Michalopoulou M, Kapetanakis S, Giovannopoulou E, Malliou P, Godolias G and Soucacos P. 2016. Reduction of falls and factors affecting falls a year after total knee arthroplasty in elderly patients with severe knee osteoarthritis. *Open Orthop J* 10: 522-531. doi: 10.2174/1874325001610010522.
4. Gage WH, Frank JS, Prentice SD and Stevenson P. 2008. Postural responses following a rotational support surface perturbation, following knee joint replacement: frontal plane rotations. *Gait Posture* 27: 286-293. doi: 10.1016/j.gaitpost.2007.04.006.
5. Gillespie LD, Gillespie WJ, Robertson MC, Lamb SE, Cumming RG, Rowe BH. 2003. Interventions for preventing falls in elderly people. Cochrane Database Syst Rev 4: CD000340. doi: 10.1002/14651858.CD000340.
6. Della Rocca GJ, Leung KS and Pape HC. 2011. Periprosthetic fractures: epidemiology and future projections. *J Orthop Trauma* 25: S66-S70. doi: 10.1097/BOT.0b013e31821b8c28.
7. Taniguchi M, Sawano S, Maegawa S, Ikezoe T and Ichihashi N. 2021. Physical activity mediates the relationship between gait function and fall incidence after total knee arthroplasty. *J Knee Surg* 34: 1205-1211. doi: 10.1055/s-0040-1702165.

8. Mawarikado Y, Inagaki Y, Fujii T, Kubo T, Kido A and Tanaka Y. 2023. Relationship between fall history and toe grip strength in older adults with knee osteoarthritis in Japan: a cross-sectional study. *PLoS One* 18: e0282944. doi: 10.1371/journal.pone.0282944.

9. Tsuyuguchi R, Kurose S, Seto T, Takao N, Fujii A, Tsutsumi H, Otsuki S and Kimura Y. 2019. The effects of toe grip training on physical performance and cognitive function of nursing home residents. *J Physiol Anthropol* 38: 11. doi: 10.1186/s40101-019-0202-5.

10. Kojima K, Kamai D, Yamamoto A, Tsuchitani Y, Kataoka H. 2021. The Effect of Toe-grasping Exercises on Balance Ability in Home-based Rehabilitation: A Randomized Controlled Trial by Block Randomization. Phys Ther Res 24: 272-279. doi: 10.1298/ptr.E10105.

11. Uritani D, Fukumoto T, Matsumoto D and Shima M. 2016. The relationship between toe grip strength and dynamic balance or functional mobility among community-dwelling Japanese older adults: a cross-sectional study. *J Aging Phys Act* 24: 459-464. doi: 10.1123/japa.2015-0123.

12. Arai R, Fuchigami M, Yamamoto K, Hatamura K, Tatsuki Y. 2022. Intra- and inter-examiner reliability and minimal detectable change for different methods of measuring toe grip strength in healthy adults. *J Phys Ther Sci* 34: 99-102. doi: 10.1589/jpts.34.99.

13. Podsiadlo D and Richardson S. 1991. The timed “up & go”: a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc* 39: 142-148. doi: 10.1111/j.1532-5415.1991.tb01616.x.

14. Hofheinz M. and Schusterschitz C. 2010. Dual task interference in estimating the risk of falls and measuring change: a comparative, psychometric study of four measurements. *Clin Rehabil* 24: 831-842. doi: 10.1177/0269215510367993.

15. Clark RD, Lord SR and Webster IW. 1993. Clinical parameters associated with falls in an elderly population. *Gerontology* 39: 117-123. doi: 10.1159/000213521.

16. McCormack HM, Horne DJ and Sheather S. 1988. Clinical applications of visual analogue scales: a critical review. *Psychol Med* 18: 1007-1019. doi: 10.1017/s0033291700009934.

17. Koblbauer IF, Lambrecht Y, van der Hulst ML, Neeter C, Engelbert RH, Poolman RW and Scholtes VA. 2011. Reliability of maximal isometric knee strength testing with modified hand-held dynamometry in patients awaiting total knee arthroplasty: useful in research and individual patient settings? A reliability study. *BMC Musculoskelet Disord* 12: 249. doi: 10.1186/1471-2474-12-249.

18. Tinetti ME, Richman D and Powell L. 1990. Falls efficacy as a measure of fear of falling. *J Gerontol* 45: P239-P243. doi: 10.1093/geronj/45.6.p239.

19. Barber SD, Noyes FR, Mangine RE, McCloskey JW and Hartman W. 1990. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clin Orthop Relat Res* 255: 204-214.

20. Faria R, Alava MH, Manca A and Wailoo AJ. 2015. NICE DSU TECHNICAL SUPPORT DOCUMENT 17: THE USE OF OBSERVATIONAL DATA TO INFORM ESTIMATES OF TREATMENT EFFECTIVENESS IN TECHNOLOGY APPRAISAL: METHODS FOR COMPARATIVE INDIVIDUAL PATIENT DATA.

21. Hicks JH. 1954. The mechanics of the foot. II. The plantar aponeurosis and the arch. *J Anat* 88: 25-30.

22. Yamashita K, Umezawa J, Nomoto Y, Ino S, Ifukube T, Koyama H, Kawasumi M and Saito M. 2002. Evaluation of falling risk by toe-gap force on aged. *Trans Soc Instrum*

Control Eng 38: 952-957.

23. Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. 2011. Gait, balance and plantar pressures in older people with toe deformities. *Gait Posture* 34: 347-351. doi: 10.1016/j.gaitpost.2011.05.023.

24. Dipietro L, Campbell WW, Buchner DM, Erickson KI, Powell KE, Bloodgood B, Hughes T, Day KR, Piercy KL, Vaux-Bjerke A and Olson RD. 2019. Physical activity, injurious falls, and physical function in aging: an umbrella review. *Med Sci Sports Exerc* 51: 1303-1313. doi: 10.1249/MSS.0000000000001942.

25. Arvin M, van Dieën JH, Faber GS, Pijnappels M, Hoozemans MJM and Verschueren SMP. 2016. Hip abductor neuromuscular capacity: a limiting factor in mediolateral balance control in older adults? *Clin Biomech* 37: 27-33. doi: 10.1016/j.clinbiomech.2016.05.015.

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Author contributions

Conceptualization: YM, YI, AK, YT; Data curation: YM, YI; Formal analysis: YM, YI; Investigation: YM, YI, TK, TF; Methodology: YM, YI, TK, TF; Project administration: YM; Resources: YM, TF; Software: YM, YI; Visualization: YM, YI; Writing – original draft: All authors; Writing – review & editing: All authors

Additional information

Assessment data is available for "S1 dataset".

Competing interests

The authors declare no competing interests.

Figure legends

Fig. 1

Towel-gathering exercise: The participants were instructed to gather a towel with their toes without lifting their toes from the floor. This training was performed in three sets using a 1-m towel in the sitting position. **a**: The feet are placed on the towel. The toes are used to gather the towel towards the participant. **b**: A 500-mL PET bottle filled with water was placed on the end of the towel as a load. **c**: Grasping and releasing a golf ball. The image shows a gold ball being gripped between the toes. Participants were instructed to grip and release the golf ball repeatedly using their toes. They performed the training for a total of 5 min. Rock-paper-scissor movements were performed using the toes (**d**: clenching the toes, **e**: raising the big toe, **f**: keeping the toes apart so that they did not touch each other). The participants practised making rock, paper, and scissors shapes with their toes. They were instructed to perform three sets of 10 repetitions of this technique.

Fig. 2.

a: The picture on the left shows the cover of the training notebook. Participants in the T-group were asked to bring the training notebook with them each time they attended outpatient physiotherapy. The page on the right describes the TGS training and notes the precautions. The precautions describe that the TGS training should be carried out in a chair with stable footing. It also describes that if toe pain or other symptoms appear, the physiotherapist in charge should be consulted.

b: Both pages are two-month calendars (example calendars are shown for the months of May and June). T-group participants were instructed to write a "○" on the days they performed the training and an "×" on the days they did not perform the training.

Fig. 3.

The study instructions were explained verbally to all eligible participants, and written informed consent was obtained. Participants were divided into two groups according to whether they wished to participate in the toe grip-related training.

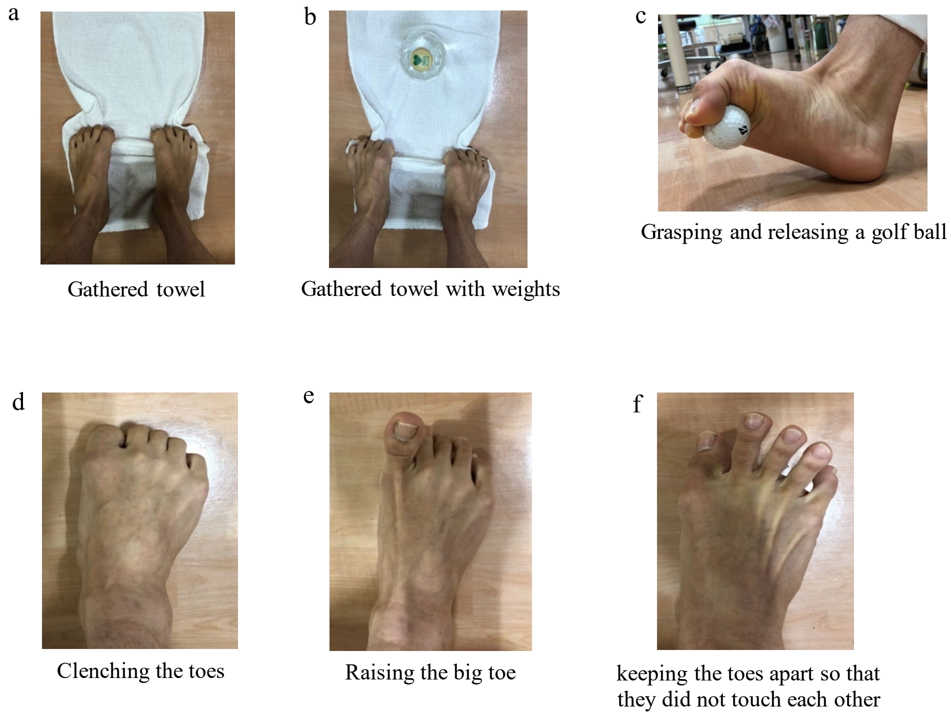
Fig. 4.

a: A toe grip dynamometer (T.K.K. 3361; Takei Scientific Instruments, Niigata, Japan) was used to measure toe grip strength. **b**: Participants sat on the edge of a seat with their trunk in a vertical position and their knees flexed approximately 90°.

Fig. 5.

Flowchart of the participants recruitment.

Fig. 1. Toe grip strength training



a Gathered towel

b Gathered towel with weights

c Grasping and releasing a golf ball

d Clenching the toes

e Raising the big toe

f keeping the toes apart so that they did not touch each other

Fig. 2. Notebook for training

a

Toe Grip Training Handbook

***Please bring this to every outpatient rehabilitation visit.**

ID: ____________________

Name: ____________________

For patients undergoing toe grip training.

1. It has already been reported that stronger toe-flexor muscles improve walking speed and are less likely to cause falls.

2. Even if you have a wound or pain in the thigh area after artificial joint surgery, you can do this training with confidence as it is toe grip training.

3. You **should carry out all training in a chair with stable footing.**

4. **The implementation period is approximately three months.** Please consult your physiotherapist about how to do it.

   ***If you experience any pain in your toe, please consult your physiotherapist!**

5. **Please mark a '○'** on the calendar for the days when it has been carried out.

b

"○" on days when you have done finger training, "×" on days when you have not done toe grip training.
Please do this at least four times a week.

May

SUN	MON	TUE	WED	THU	FRI	SAT
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30

"○" on days when you have done finger training, "×" on days when you have not done toe grip training.
Please do this at least four times a week.

June

SUN	MON	TUE	WED	THU	FRI	SAT
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30				

Fig. 3. The study protocol from hospitalization to grouping

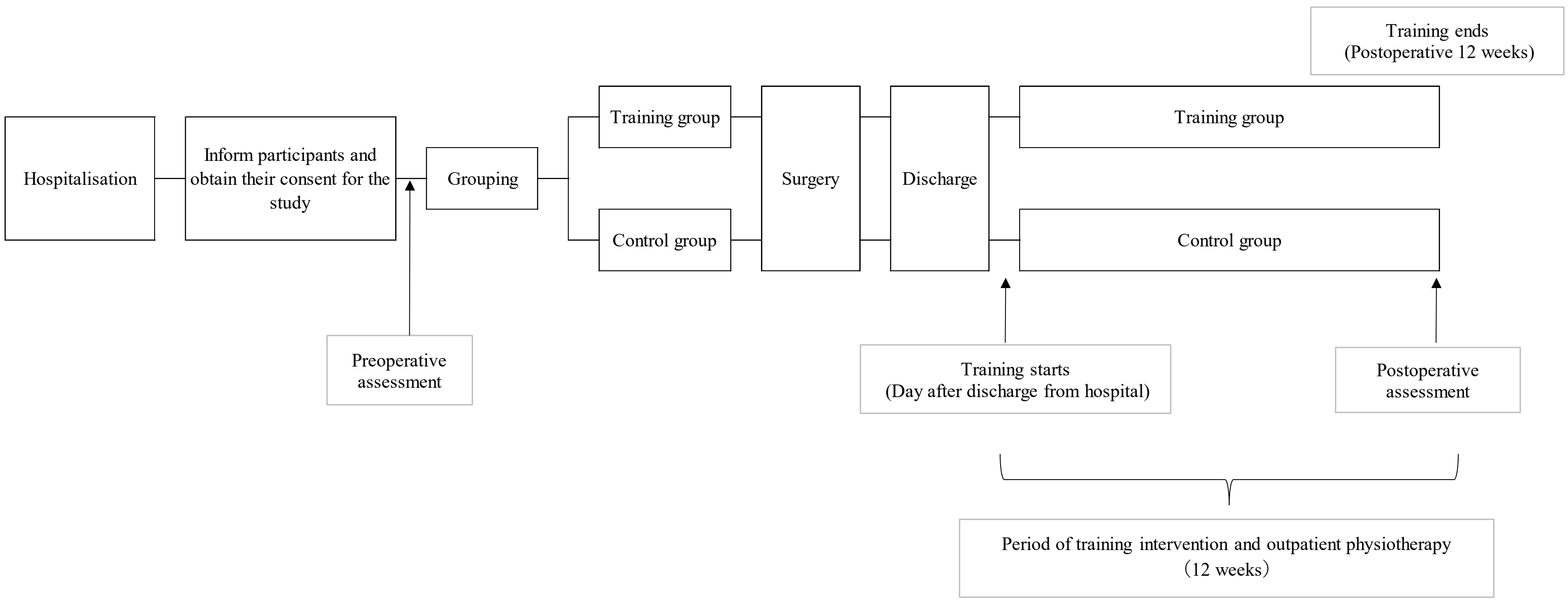


Fig. 4. The method of toe grip strength assessment

Fig 5. Flowchart of the participants recruitment

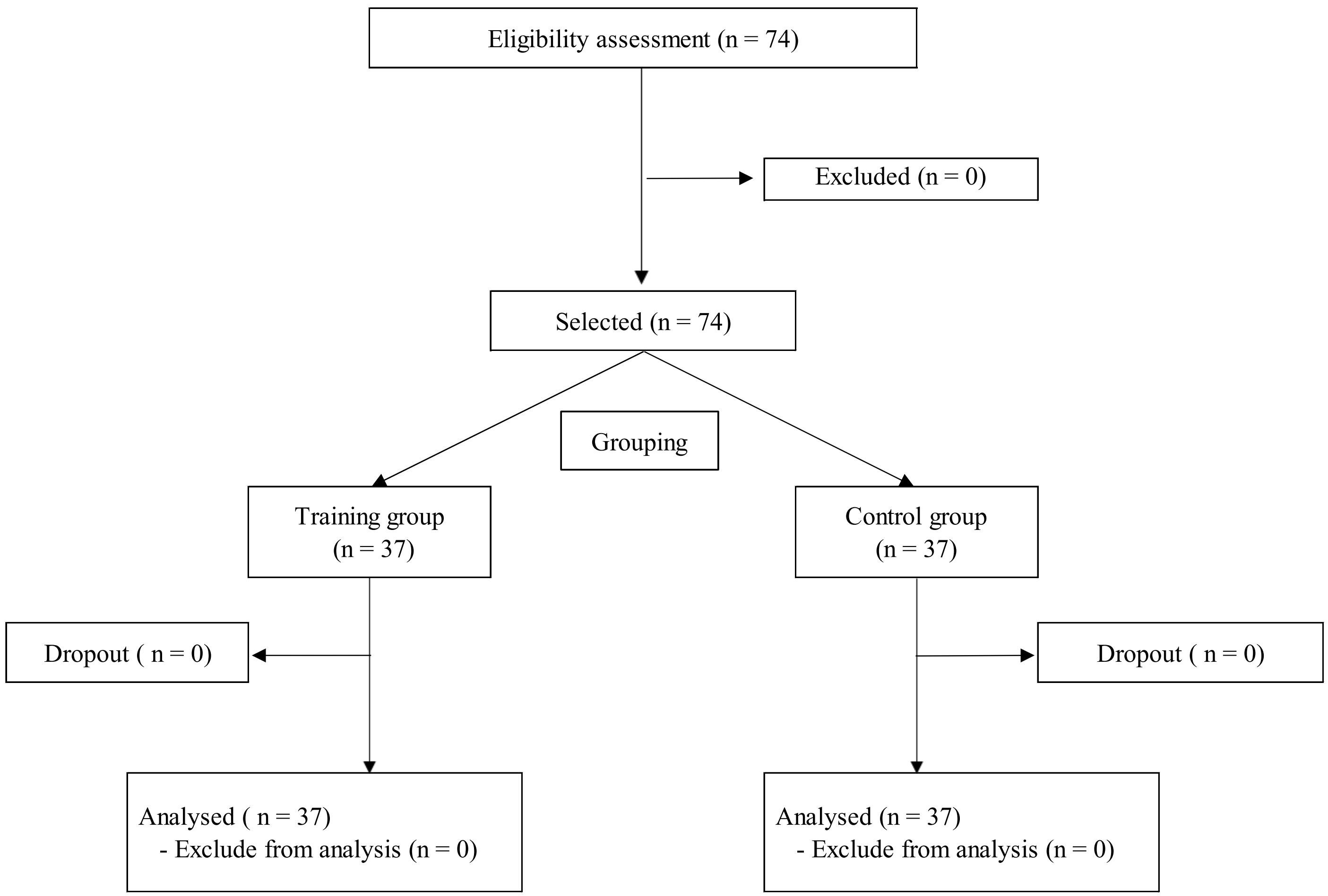


Table 1. A comparison of baseline values between training group and the control group

		Training group (n=37)			Control group (n=37)			p value
Age, year		75.1	±	6.3	75.4	±	5.8	0.696 m
Height, cm		155.1	±	7.6	154.5	±	8.1	0.770 m
Weight, kg		61.4	±	10.7	61.7	±	11.3	0.829 m
Body mass index, kg/m²		25.4	±	3.5	25.8	±	3.6	0.683 u-t
Gender, male/female		8 / 29			6 / 31			0.553c
K-L grade (affected side) , Ⅰ/Ⅱ/Ⅲ/Ⅳ		0 / 0 / 3 / 33			0 / 0 / 6 / 31			0.496c
K-L grade (unaffected side) , Ⅰ/Ⅱ/Ⅲ/Ⅳ		1 / 2 / 21 / 13			1 / 0 / 19 / 17			0.452c
Type of implant, PS / CS		34 / 3			30 / 7			0.174c
The affected side, right/ left		21/16			20/17			0.815c
Number of hospitalization days, n		15.9	±	2.8	16.4	±	4.1	0.279 m
Walking style preoperatively, cane/ walking alone		7 / 30			7 / 30			1.000c
Preoperative fall, presence/absence		9 / 28			11 / 26			0.601c
TUG-T, sec		11.9	±	3.5	12.6	±	4.5	0.585 m
TGS, kg	affected side	7.9	±	4.2	7.2	±	3.9	0.456 m
	unaffected side	8.6	±	3.8	8.2	±	4.9	0.446 m
Rest pain, mm	affected side	16.9	±	24.4	17.0	±	21.9	0.780 m
	unaffected side	3.6	±	12.7	7.5	±	15.2	0.308 m
Walking pain, mm	affected side	53.2	±	23.6	46.9	±	24.2	0.261 u-t
	unaffected side	16.9	±	21.6	17.8	±	22.9	0.726 m
IKES, kgf	affected side	13.7	±	6.0	15.9	±	9.2	0.615 m
	unaffected side	17.6	±	6.9	17.6	±	9.4	0.650 m
mFES, points		104.3	±	32.5	92.9	±	37.5	0.214 m
KOOS, %	Symptoms	63.2	±	17.4	59.8	±	17.9	0.413 u-t
	Pain	50.5	±	18.3	44.5	±	17.6	0.161 u-t
	ADL	61.8	±	18.4	56.6	±	18.3	0.223 u-t
	Sport/Rec	23.8	±	22.7	18.1	±	19.6	0.275 m
	QOL	30.8	±	17.1	27.9	±	14.4	0.756 m

Data are presented as mean ± SD and numbers.The significance level is 5%.
The statistical analysis used in the unpaired t-test, the Mann-Whitney U test and the chi-square test
u-t: The unpaired t-test, m; Mann–Whitney U test, c; Chi-squared test
K-L grade: Kellgren-Laurence grading, TUG-T: Timed up and go test, TGS: Toe grip strength,
IKES: Isometric knee extension strength, mFES: modified fall efficacy scale,
KOOS: Knee injury and osteoarthritis outcome score

Table 2. Measurements performed on the two groups

		Training group (n=37)							Control group (n=37)						
		Pre-evaluation			Post 3M evaluatio			p value	Pre-evaluation			Post 3M evaluatio			p value
TUG-T		11.9	±	3.5	9.1	±	1.5	0.001^{w}	12.6	±	4.5	11.4	±	3.0	0.014^{w}
TGS	affected side	7.9	±	4.2	10.3	±	4.7	0.001^{w}	7.2	±	3.9	7.9	±	4.9	0.078^{w}
	unaffected side	8.6	±	3.8	11.4	±	4.8	$0.001^{p\text{-}t}$	8.2	±	4.9	8.2	±	5.1	0.850^{w}
Rest pian	affected side	16.9	±	24.4	6.1	±	14.7	0.400^{w}	17.0	±	21.9	8.1	±	14.9	0.001^{w}
	unaffected side	3.6	±	12.7	1.8	±	6.3	0.253^{w}	7.5	±	15.2	3.0	±	10.2	0.050^{w}
Walking pain	affected side	53.2	±	23.6	9.7	±	14.7	0.001^{w}	46.9	±	24.2	9.1	±	12.1	0.001^{w}
	unaffected side	16.9	±	21.6	6.6	±	12.2	0.001^{w}	17.8	±	22.9	2.4	±	7.4	0.016^{w}
IKES	affected side	13.7	±	6.0	14.2	±	6.6	$0.580^{p\text{-}t}$	15.9	±	9.2	14.9	±	7.5	0.563^{w}
	unaffected side	17.6	±	6.9	19.2	±	7.4	$0.078^{p\text{-}t}$	17.6	±	9.4	17.9	±	8.9	0.563^{w}
mFES		104.3	±	32.5	123.5	±	19.4	0.002^{w}	92.9	±	37.5	112.2	±	28.3	0.001^{w}
	Symptoms	63.2	±	17.4	75.3	±	16.5	0.005^{w}	59.8	±	17.9	68.2	±	16.4	0.035^{w}
	Pain	50.5	±	18.3	80.2	±	14.4	0.001^{w}	44.5	±	17.6	70.1	±	18.4	0.001^{w}
KOOS	ADL	61.8	±	18.4	80.6	±	14.2	$0.001^{p\text{-}t}$	56.6	±	18.3	73.2	±	14.6	0.001^{w}
	Sport/Rec	23.8	±	22.7	32.3	±	30.4	0.111^{w}	18.1	±	19.6	28.9	±	23.6	0.075^{w}
	QOL	30.8	±	17.1	55.9	±	20.2	0.001^{w}	27.9	±	14.4	47.5	±	20.8	$0.001^{p\text{-}t}$

Data are presented as mean ± SD.The significance level is 5%.
The statistical analysis used in Wilcoxon signed rank test and the paired t-test.
w; Wilcoxon signed rank test, p-t; The paired t-test
TUG-T: Timed up and go test, TGS: Toe grip strength, IKES: Isometric knee extension strength, mFES: modified fall efficacy scale,
KOOS: Knee injury and osteoarthritis outcome score

Table 3. Comparison of changes(Δ) between training group and control group

		Training group (n=37)			Control group (n=37)			p value
Δ TUG-T		-2.8	±	3.2	-1.2	±	2.6	0.007^m
Δ TGS	affected side	2.4	±	3.6	0.7	±	2.5	0.007^m
	unaffected side	2.7	±	3.4	0.0	±	2.4	0.001^m
Δ rest pain	affected side	-10.7	±	17.8	-8.9	±	23.2	0.222^m
	unaffected side	-1.8	±	9.6	-4.5	±	13.2	0.708^m
Δ walking pain	affected side	-42.1	±	25.5	-37.9	±	30.0	0.515^u-t
	unaffected side	-10.2	±	24.0	-15.4	±	23.2	0.950^m
Δ IKES	affected side	0.5	±	5.7	-1.0	±	5.5	0.272^m
	unaffected side	1.7	±	5.6	0.2	±	4.9	0.240^u-t
Δ mFES		19.2	±	35.2	19.3	±	32.7	0.927^m
Δ KOOS	Symptoms	12.1	±	23.0	8.4	±	25.0	0.514^u-t
	Pain	29.7	±	18.2	25.6	±	26.5	0.438^u-t
	ADL	18.8	±	16.0	16.6	±	24.1	0.652^u-t
	Sport/Rec	8.5	±	37.3	10.8	±	33.2	0.780^u-t
	QOL	25.2	±	25.8	19.6	±	21.6	0.316^u-t

Data are presented as mean ± SD.The significance level is 5%.
The statistical analysis used in the unpaired t-test and the Mann-Whitney U test.
u-t: The unpaired t-test, m; Mann–Whitney U test
TUG-T: Timed up and go test, TGS: Toe grip strength, IKES: Isometric knee extension strength, mFES: modified fall efficacy scale, KOOS: Knee injury and osteoarthritis outcome score

Table 4. Correlations between the degree of change(Δ) in improvement for each value in training group

	Age	BMI	Δ TGS		Δ rest pain		Δ walking pain		Δ IKES		Δ mFES
			affected side	unaffected side	affected side	unaffected side	affected side	unaffected side	affected side	unaffected side	
Δ TUG-T	-0.264	-0.085	-0.406*	-0.072	-0.004	0.139	0.144	0.087	-0.162	-0.103	0.302

Data are presented as the value of correlation coefficient. *: p<0.05

TUG-T: Timed up and go test, BMI: Body mass index, TGS: Toe grip strength, IKES: Isometric knee extension strength, mFES: modified fall efficacy scale

Table 5. Comparison of falls and walking style in training group and control group

	Training group (n=37)	Control group (n=37)	p value
Preoperative fall, presence/absence (% faller)	9 / 28 (24.3%)	11 / 26 (29.7%)	0.601[c]
Postoperative fall (3 months), presence/absence (% faller)	1/36 (2.7%)	5/32 (13.5%)	0.100[f]
Postoperative fall (12 months), presence/absence (% faller)	6/31 (16.2%)	14/23 (37.8%)	0.036[c]
Walking style preoperatively, cane/ walking alone	7 / 30	7 / 30	1.000[c]
Walking style at 3 month postoperatively, cane/walking alone	5/32	8/29	0.359[c]

Data are presented as numbers.The significance level is 5%.
The statistical analysis used in Chi-squared test and Fisher's exact test.
c; Chi-squared test, f; Fisher's exact test

Group	Age	Height	Weight	BMI	Gender	Type of implant	Affected side	Knee Injury and Osteoarthritis Outcome Score (KOOS)										modified Fall Efficacy Scale (mFES)			Occurrence of falls			Walking pain	Rest pain	Walking pain	Rest pain	Walking pain	Rest pain	Walking pain	Rest pain	Δwalking pain	Δrest pain	Δwalking pain	Δrest pain	Isometric knee extension (IKES)						Toe grip strength (TGS)						Timed up and go test (TUG)			Walking style		Hospitalization days	Kellgren-Laurence grading (K-L grade)	
								Preoperative					3 months post-operatively					Preoperative	3 months post-operatively	Δ（3M-Pre）	Preoperative	3 months post-operatively	12 months post-operatively	Preoperative				3 months post-operatively								Preoperative		3 months post-operatively		Δ（3M-Pre）		Preoperative		3 months post-operatively		Δ（3M-Pre）		Preoperative	3 months post-operatively	Δ(3M-Pre)	Preoperative	3 months post-operatively		Preoperative	
								Symptoms	Pain	ADL	Rec	QOL	Symptoms	Pain	ADL	Rec	QOL							affected side		unaffected side		affected side		unaffected side		affected side		unaffected side		affected side	unaffected side	affected side	unaffected side	affected side	unaffected side	affected side	unaffected side	affected side	unaffected side	affected side	unaffected side							affected side	unaffected side
T-group	76	177.2	71.2	22.7	M	PS	L	71.4	58.3	57.4	0.0	56.3	85.7	91.7	95.6	80.0	81.3	95	139	44	No	No	No	70	0	33	0	0	0	0	0	-70	0	-33	0	28.3	31.6	26.35	25.1	-1.95	-6.5	17.7	17.2	18.0	17.1	0.30	-0.10	11.825	8.09	-3.735	Walking alone	Walking alone	16	4	3
T-group	82	153.1	56.4	24.1	M	PS	R	57.1	63.9	77.9	25.0	50.0	92.9	88.9	85.3	70.0	56.3	137	140	3	No	No	No	50	0	0	0	0	0	0	0	-50	0	0	0	17.35	19.3	11.5	15.1	-5.85	-4.2	12.0	15.8	18.4	19.4	6.40	3.60	10.7	9.335	-1.365	Walking alone	Walking alone	19	4	1
T-group	81	148.6	47.85	21.7	F	PS	R	32.1	41.7	55.9	40.0	18.8	89.3	97.2	94.1	90.0	81.3	37	139	102	No	No	No	50	0	0	0	0	0	0	0	-50	0	0	0	11.5	19	15.95	14.15	4.45	-4.85	11.8	13.0	11.5	10.0	-0.30	-3.00	9.25	9.05	-0.2	Walking alone	Walking alone	20	4	2
T-group	68	154.3	70.1	29.4	F	PS	L	60.7	55.6	79.4	40.0	18.8	96.4	91.7	91.2	50.0	81.3	119	140	21	No	No	No	91	56	41	0	0	0	9	0	-91	-56	-32	0	12.15	16.4	13	16.8	0.85	0.4	8.1	9.6	7.4	11.6	-0.70	2.00	6.035	8.41	2.375	Walking alone	Walking alone	18	4	3
T-group	76	142.4	43.5	21.5	F	PS	R	82.1	55.6	69.1	5.0	12.5	64.3	83.3	72.1	20.0	62.5	120	109	-11	No	No	No	70	50	10	10	0	0	0	0	-50	-50	-10	-10	3.35	15.3	13.2	21.8	9.85	6.5	4.1	8.3	12.2	11.7	8.10	3.40	18.865	7.54	-11.325	Walking alone	Walking alone	9	4	3
T-group	82	148.1	64.4	29.4	F	PS	L	21.4	25.0	54.4	10.0	31.3	71.4	88.9	86.8	0.0	43.8	140	140	0	No	No	No	50	0	0	0	0	0	0	0	-50	0	0	0	14.05	10.85	-7.5	15.2	-21.55	4.35	6.4	5.8	8.7	9.8	2.30	4.00	12.115	9.2	-2.915	Walking alone	Walking alone	15	4	4
T-group	73	168.3	59.1	20.9	M	CS	R	46.4	36.1	61.8	40.0	43.8	89.3	80.6	95.6	85.0	93.8	37	140	103	No	No	No	20	9	0	0	9	0	0	0	-11	-9	0	0	13.4	26.95	16.7	31.1	3.3	4.15	8.0	7.2	12.3	14.9	4.30	7.70	11.885	11.56	-0.325	Walking alone	Walking alone	15	4	3
T-group	76	149.1	60.8	27.3	F	PS	R	71.4	38.9	47.1	45.0	43.8	89.3	72.2	76.5	75.0	56.3	140	139	-1	Yes	No	No	75	35	55	0	5	5	25	15	-70	-30	-30	15	18.4	18.55	16.7	20.5	-1.7	1.95	11.0	12.9	12.9	15.6	1.90	2.70	12.115	11.1	-1.015	Walking alone	Walking alone	15	4	4
T-group	69	147.5	58.1	26.7	F	PS	L	67.9	41.7	67.6	5.0	18.8	60.7	77.8	88.2	0.0	56.3	118	128	10	Yes	No	No	75	35	55	0	5	5	25	15	-70	-30	-30	15	18.4	18.55	16.7	20.5	-1.7	1.95	8.3	9.1	14.9	12.6	6.60	3.50	12.115	8.5	-3.615	Cane	Cane	16	4	4
T-group	82	150.8	54.8	24.1	F	CS	R	60.7	44.4	55.9	50.0	31.3	67.9	47.2	72.1	25.0	37.5	112	114	2	No	No	No	71	0	0	0	0	4	0	0	-66	4	0	0	7.9	24.85	7.9	24.85	0	0	10.3	7.9	12.6	14.8	2.30	6.90	15.775	9.64	-6.135	Walking alone	Walking alone	15	4	3