Loading of the artificial knee during early rehabilitation and physiotherapy

an in vivo study

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Aims

This retrospective observational study aimed to determine the in vivo joint loads in the knee after total knee arthroplasty during early postoperative rehabilitation involving different physiotherapy exercises and to analyze how these loads change over the first three weeks postoperatively.

Methods

Nine patients (six males, three females) with a primary instrumented total knee replacement participated in the study. A total of 19 selected physical therapy exercises of varying load levels were performed on the ninth (SD 3) and 21st (SD 6) postoperative day. During these sessions, the peak resultant knee contact force ($F_{res\ max}$) and loading patterns were measured to assess joint loading dynamics.

Results

$F_{res\ max}$ varied across different exercises, ranging from a minimum of 15% body weight (% BW) during seated leg swings to a maximum of 195% BW during stair ascent. Joint loads increased from the ninth to the 21st postoperative day for all activities, except for a few relaxed status exercises where a decrease was observed. Load-bearing activities with crutches had the highest knee joint loads.

Conclusion

All exercises remained below the forces of walking on ground level indicating safety for the postoperative rehabilitation. Physical therapists should consider these loads in relation to daily activities when designing treatment plans also referring to the different loads in different exercises.

Take home message

- This study provides detailed in vivo data on knee joint loading during early postoperative rehabilitation following total knee arthroplasty (TKA), contributing to evidence-based optimization of physiotherapy protocols.
- Relaxed and swelling-reduction exercises were associated with low joint contact forces, making them suitable for the early postoperative phase to facilitate tissue healing while minimizing mechanical stress.
- Load-bearing activities, including crutch-assisted walking and stair climbing, resulted in moderate to high joint loads but remained below those of level walking, underscoring their importance for

functional recovery when appropriately integrated into individualized rehabilitation plans.

Introduction

Total knee arthroplasty (TKA) is one of the most common surgical procedures worldwide, primarily indicated for osteoarthritis, a prevalent joint disease that increases with age.[1] Following TKA or fracture fixation, the recovery of joint function, pain reduction, patient satisfaction, and implant longevity are decisive factors for surgical success.[2] Restoring the ability to perform activities of daily living (ADL) is the primary goal of the surgical intervention. Early mobilization, rehabilitation, and physiotherapy training are essential elements.[3-5] In particular, cementless arthroplasty and fracture fixation entail a vulnerable phase of osseointegration and fracture healing, respectively. While immediate full weight-bearing is now generally preferred for primary cemented TKA, individualized rehabilitation planning remains critical, particularly for uncemented prostheses and periarticular fractures, where optimal loading strategies are less defined.[6-9] Also in cemented arthroplasty, where primary stability of the implants is given, in vivo joint loads during the rehabilitative procedures can provide insights into stress on still healing soft-tissues in early rehabilitation phases. By systematically quantifying in vivo joint loads during early postoperative rehabilitation, this study provides fundamental data on how different exercises influence mechanical stress on the knee joint.

Different in vivo studies using instrumented knee implants have already shown that joint contact forces frequently exceed body weight (BW).[10-14] Level walking can load the knee joint with up to 280% of the patient's BW,[13,15] while descending stairs can impose up to 350% BW.[12] However, there remains a lack of understanding regarding realistic joint loading during early rehabilitation and physiotherapy training. Furthermore, postoperative load specifications provided by surgical guidelines typically do not account for additional in vivo forces resulting from muscle co-contractions.[16] Existing studies of our group also suggest a correlation between pre-existing fatty muscle degeneration, the extent of intraoperative muscle damage, and increased in vivo contact forces.[17-19] Prior research has primarily focused on in vivo data during selected sporting activities and ADL,[12,13,20-24] largely neglecting knee joint loads during rehabilitation and physiotherapy training in the early postoperative phase.

The initial phase of recovery after knee joint arthroplasty is crucial, even with cemented prostheses, as seen in all our patients, where primary stability is established, but further healing is required.[25-27] Moreover, the periarticular muscles spanning the joint are affected by surgery, with their injury and impairment being responsible for increasing stress on the prosthesis.[17-19]

In recent years, several fundamental therapeutic concepts in physiotherapy have been developed for the postoperative care and rehabilitation of patients undergoing TKA. However, treatment approaches vary widely among clinics.[3,4,28,29] Hence, the aim of the study was to determine the in vivo joint loads acting at the knee joint after TKA, during the early phase of rehabilitation and physiotherapy training. A secondary aim of this study was to determine the change in TKA loading during the postoperative recovery, to obtain more detailed information on the actual load profiles within the joint over time. In the context of the existing literature on forces acting on the knee joint in vivo,[10-14] we formulated the following research questions: 1) what are the in vivo loads acting on the knee joint after TKA, during the early phase of rehabilitation and physiotherapy training?; 2) what changes can be observed in the in vivo joint loads during physiotherapy training over the early postoperative phase?

Methods

Participants

Six male and three female patients with an instrumented TKA participated in this study. The use of instrumented knee prostheses for the in vivo measurement of joint loads requires specialized implants and complex telemetric systems. Due to the limited availability of these implants and the complex technical implementation, the sample size of this study is comparatively small. Patient characteristics are shown in Table I. The clinical study was approved by the Charité Ethics Committee (EA2/057/09) and registered at the 'German Clinical Trials Register' (DRKS00000563). All subjects gave their written informed consent to participate.

Inclusion criteria were the need for a primary TKA due to osteoarthritis, the ability to perform the required physiotherapy exercises, and the commitment and motivation to participate in a long-term clinical study. Exclusion criteria were the presence of other active implants (e.g. cardiac pacemakers), inflammatory arthritis, and neurological or muscular diseases. All TKA procedures were performed using the medial parapatellar approach and the tibia-first gap-balancing technique by two experienced surgeons (see Acknowledgements) at a single institution (Sana Kliniken Sommerfeld, Germany).

Design

A total of 19 physiotherapy exercises were selected (Table II) and divided into five typical groups for postoperative mobilization and muscle training: 1) relaxation; 2) exercises to reduce swelling; 3) isometric exercises; 4) dynamic exercises; and 5) exercises on crutches.

The chosen exercises represent standard rehabilitation protocols for early mobilization after TKA as for example described by the American Academy of Orthopaedic Surgeons.[30] The selection aimed to include a spectrum of low- to high-load activities to provide comprehensive data on knee joint stress.

The measurements were conducted during physiotherapy training at two postoperative timepoints during rehabilitation, the first being nine days (SD 3) (D9) and the second 21 days (SD 6) (D21). Day nine represents an initial recovery stage with limited mobility, whereas day 21 corresponds to an advanced phase with increased functional demands.

All measurements were performed with several repetitions in each category and were instructed and monitored by a physiotherapist (see Acknowledgements).

Outcome measures

In vivo joint loads were measured using instrumented knee implants (INNEX FIXUC; Zimmer Biomet, Switzerland), featuring a cruciate-sacrificing design with an ultracongruent

Table I. Patient characteristics.

Patient	K1L	K2L	K3R	K4R	K5R	K6L	K7L	K8L	K9L	Mean (SD)
Sex	M	M	M	F	M	F	F	M	M	
Height, cm	177	171	175	170	175	174	166	174	166	172 (4)
Age, yrs	62	71	70	63	60	65	74	70	75	68 (5)
Body weight, kg	98	89	96	92	97	77	71	81	103	89 (11)
BMI, kg/m^2	31	30	31	32	31	25	26	27	37	30 (3)

F, female; K, knee; L, left; M, male; R, right.

Table II. Summary of the performed exercises.

Group	Exercise
Relaxed	a) Relaxed lying (RelLyi)
	b) Relaxed lying with two towels rolled up under the heels (RelLyiTow)
	c) Sitting on the edge of the bench with hanging legs (RelSit)
Exercises to reduce swelling	a) Lying with dorsiflexion/plantarflexion in the ankle joint (LyiFlexAnk)
	b) Sitting with hanging legs and performing dorsiflexion/plantarflexion (SitFlexAnk)
Isometric exercises	a) Isometric contraction with straight knee in lying position (LyiIso)
	b) Isometric contraction with straight knee and isometric hip abduction (LyiIsoHipAbd); the therapist applies resistance to the subject's leg, pushing on the lateral side to achieve isometric hip abduction
	c) Isometric contraction with straight knee and isometric hip adduction (LyiIsoHipAdd); the therapist applies resistance to the subject's leg, pushing on the medial side to achieve isometric hip adduction
Dynamic exercises	a) Lying with sliding heel on the bench from knee extension to maximum flexion and including dorsal extension (LyiHeelSli); variation: additional resistance on the lower leg by the therapist (LyiHeelSliRes)
	b) Supine position with straight legs and ankle on a gymnastic ball (mean 65 cm) with pressure in the direction of the ball (LyiExtGymBall)
	c) Supine position with bent legs and ankle on an gymnastic ball (mean 65 cm) with pressure in the direction of the ball (LyiFlexGymBall)
	d) Sitting with swinging legs (SwingLeg)
	e) Sitting and bring ipsilateral leg into maximum extension (SitExtIpsi) 1. Performed quickly (SitExtIpsiFast) 2. With thigh elevated at the same time (SitExtThighLift) 3. Bring both legs into extension at the same time (SitExtBoth) 4. Bring both legs into extension at the same time – quickly (SitExtBothFast)
Exercises on crutches	a) 3-point gait with crutches (3PGait)
	b) 4-point gait with crutches (4PGait)
	c) Walking upstairs with crutch ipsilateral and railing contralateral (StairAscendCrutchOne)
	d) Walking upstairs with crutches on both sides (StairAscendCrutchTwo)
	e) Walking downstairs with crutch ipsilateral and railing contralateral (StairDescendCrutchOne)
	f) Walking downstairs with crutches on both sides (StairDescendCrutchTwo)

tibial inlay.[31] The implant is equipped with an induction coil, telemetric data transmission, and six strain gauges. Load-dependent deformation of the implant component is detected by these strain gauges, allowing calculation of six different load components.[32] The telemetry and external equipment were previously published in detail.[33] All patients were videotaped during the measurements and the telemetric load signals were recorded simultaneously on video.

The coordinate system of the instrumented knee implant is tibia-fixed and positioned at the lowest point of the implant inlay, with the Z-axis oriented along the axis of the implant component. The force components F_x, F_y, and F_z

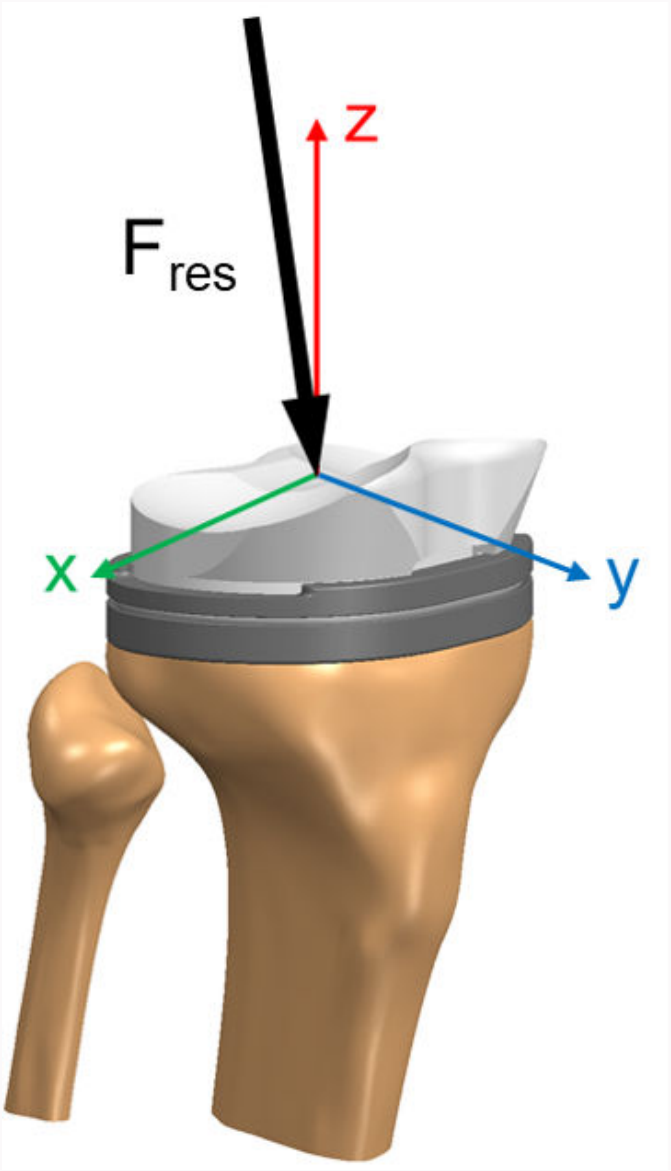

Fig. 1
Coordinate system of the instrumented knee implant. F_{res}, resultant force.

act in lateral, anterior, and superior directions relative to the tibial plateau (Figure 1). Resultant forces (F_{res}) are calculated as the square root of the sum from the three force components.[32] In this study, our focus was on determining the maximum resultant contact force ($F_{res\ max}$) only. Forces measured on the left knee are mirrored to the right side and all forces are reported in percentage of the patient's body weight (% BW).

Statistical analysis

The time loading patterns of the different activities were intra-individually averaged over the entire exercise using a dynamic time-warping procedure,[34] to create typical individual load time patterns. Subsequently the inter-individual knee joint loads were averaged using the intra-individual determined joint loads. Individual peak loads were related to the average peak values from all investigated trials. The $F_{res\ max}$ refers to the highest loads observed across all subjects and trials studied and is presented as the mean value. Additionally, the 95% CI was calculated. Since not all patients performed every exercise, $F_{res\ max}$ and CI may differ between the individual observation of an exercise and the comparison between the measurement days and between the different exercises. All statistical analyses and tests were performed using a non-parametric Wilcoxon signed-rank test (Wilcoxon matched pairs test, significance threshold: $p = 0.05$), using SPSS v26 (IBM, USA).

Results

In vivo load data were collected on the two above stated postoperative timepoints using instrumented knee joint implants to analyze load development and potential changes during the healing phase. In total, 19 common postoperative physiotherapy exercises were investigated. Figure 2 illustrates averaged activity-specific time load patterns for each exercise category, categorized by typical groups for postoperative mobilization and muscle training.

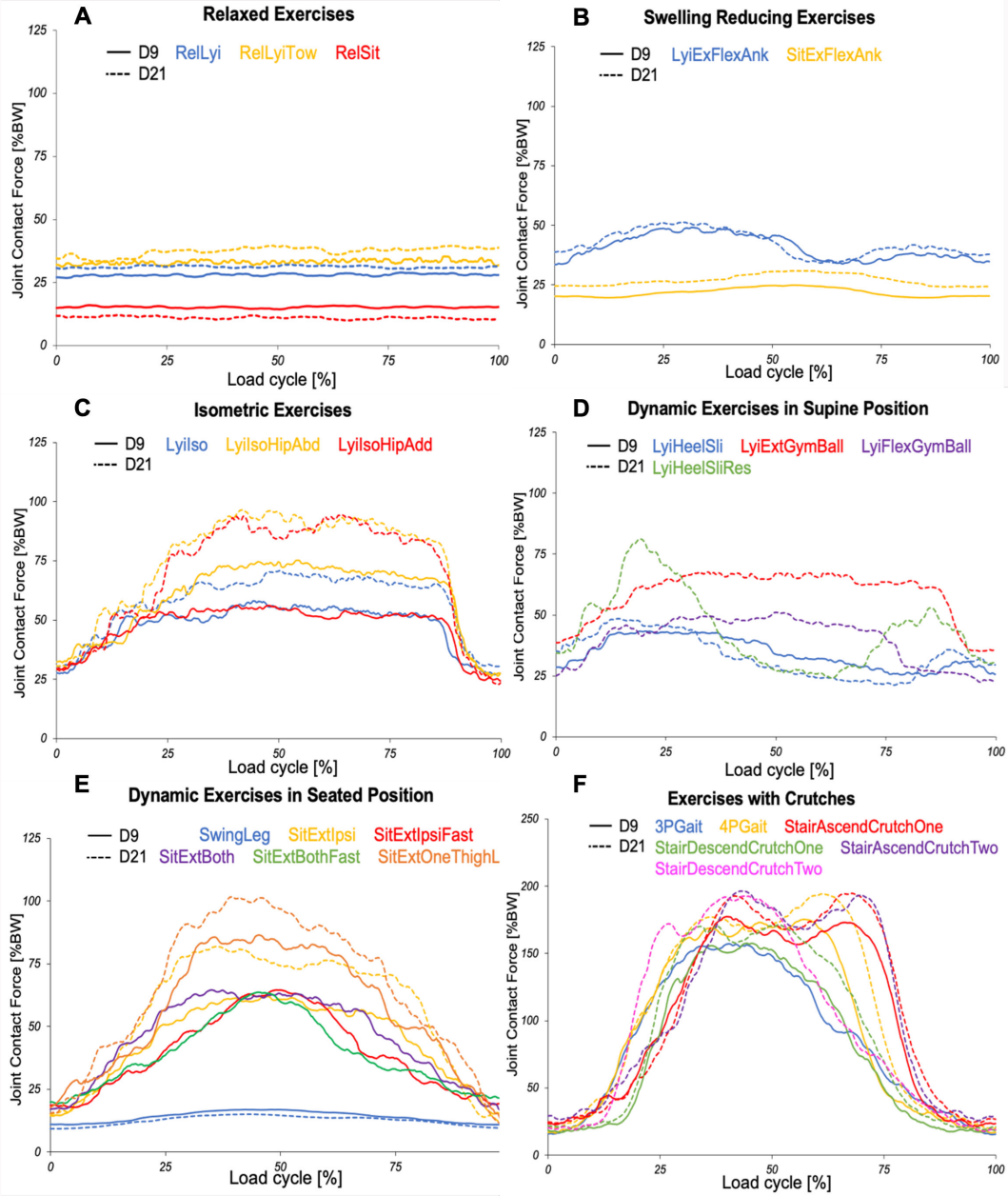

Fig. 2
Comparison of the load cycle and the resultant forces in each performed exercise: a) relaxed exercies, b) swelling reducing exercises, c) isometric exercises, d) dynamic exercises in supine position, e) dynamic exercises i seated position, and f) exercises with crutches. BW, body weight; D, day; LyiExtGymBall, supine position with straight legs and ankle on a gymnastic ball (65 cm) with pressure in the direction of the ball; LyiFlexAnk, lying with dorsiflexion/plantarflexion in the ankle joint; LyiFlexGymBall, supine position with bent legs and ankle on a gymnastic ball (65 cm) with pressure in the direction of the ball; LyiHeelSli, lying with sliding heel on the bench from knee extension to maximum flexion and including dorsal extension; LyiHeelSliRes, variation: additional resistance on the lower leg by the therapist; LyiIso, isometric contraction with straight knee in lying position; LyiIsoHipAbd, isometric contraction with straight knee and isometric hip abduction; LyiIsoHipAdd, isometric contraction with straight knee and isometric hip adduction; P, point; RelLyi, relaxed lying; RelLyiTow, relaxed lying with two towels rolled up under the heels; RelSit, relaxed sitting; SitExtIpsi, sitting and bring ipsilateral leg into maximum extension; SitFlexAnk, sitting with hanging legs and performing dorsiflexion/plantarflexion.

In vivo knee joint loads during early rehabilitation and physiotherapy

Relaxed and swelling reduction exercises

- $F_{res\ max}$ for relaxed sitting significantly decreased from 17% BW (95% CI 11.1 to 22.9) on day nine to 13% BW (95% CI 9.5 to 16.5) on day 21 ($p = 0.012$) (Figure 2a).
- No significant changes were observed in relaxed lying, although a trend towards increased $F_{res\ max}$ was seen in lying with two towels under the heels (Figure 2b).

Isometric exercises

- Lying isometric contraction showed a significant increase in $F_{res\ max}$ from 59% BW (95% CI 51.2 to 66.8) on day nine to 72% BW (95% CI 60.2 to 83.8) on day 21 ($p = 0.028$) (Figure 2c).
- Seated ipsilateral leg extension significantly increased from 63% BW (95% CI 52.5 to 73.5) to 82% BW (95% CI 66.4 to 97.6) ($p = 0.018$) (Figure 2e).

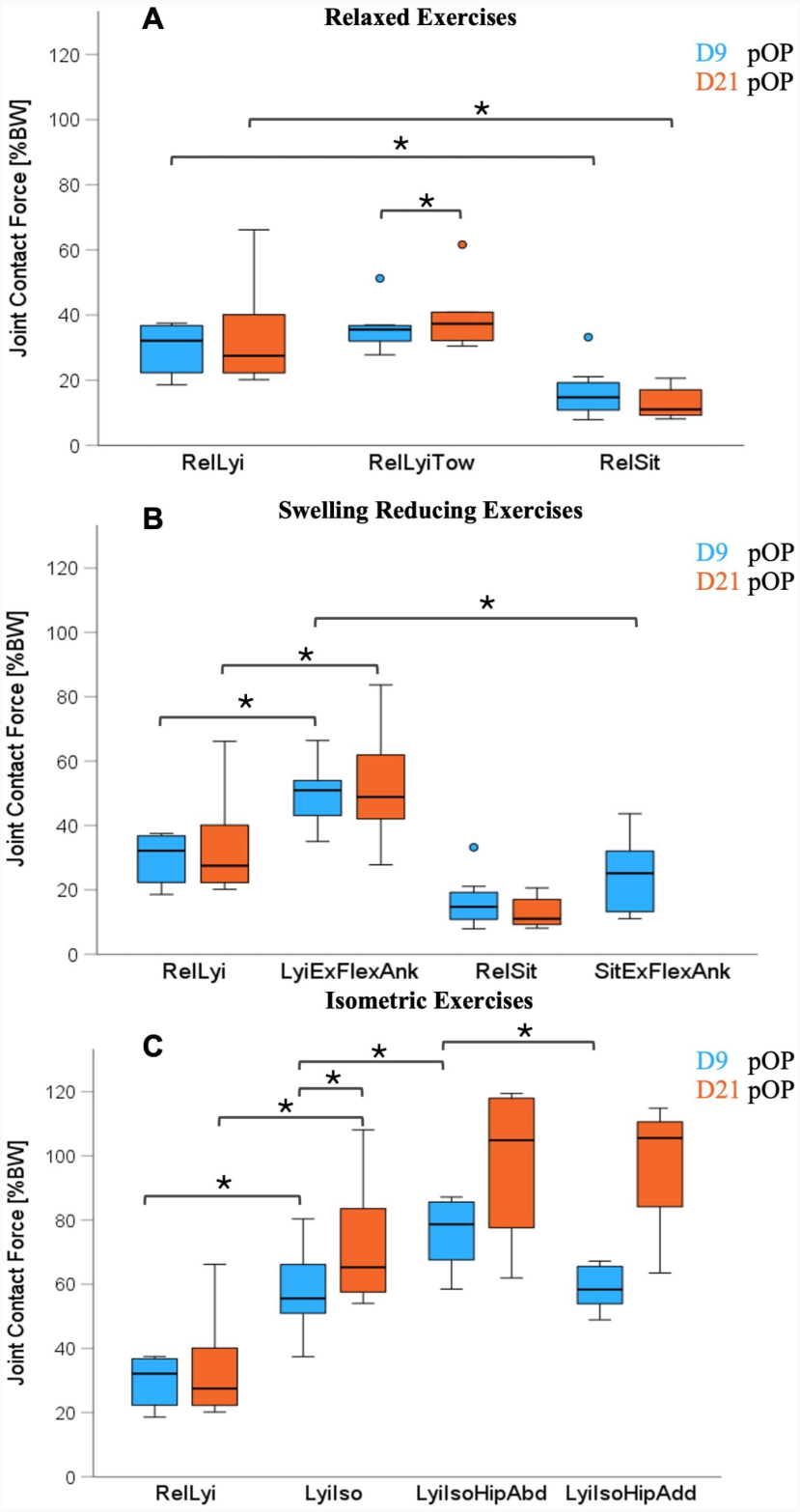

Fig. 3
Change of maximum resultant contact force (Fres max) during relaxed, swelling reducing, and isometric exercises from day 9 (D9) to day 21 (D21). *p ≤ 0.05. BW, body weight; LyiFlexAnk, lying with dorsiflexion/plantarflexion in the ankle joint; LyiIso, isometric contraction with straight knee in lying position; LyiIsoHipAbd, isometric contraction with straight knee and isometric hip abduction; LyiIsoHipAdd, isometric contraction with straight knee and isometric hip adduction; pOP, postoperative; RelLyi, relaxed lying; RelLyiTow, relaxed lying with two towels rolled up under the heels; RelSit, relaxed sitting; SitFlexAnk, sitting with hanging legs and performing dorsiflexion/plantarflexion.

- Additional resistance during isometric hip abduction led to a notable increase in $F_{res\ max}$ from 76% BW (95% CI 68 to 84) to 98% BW (95% CI 75.5 to 120.5) on day 21 (p = 0.068), albeit without statistical significance.

Dynamic exercises

- Leg swinging exhibited a minor reduction in $F_{res\ max}$ from 17% BW (95% CI 13.5 to 20.5) on day nine to 15% BW

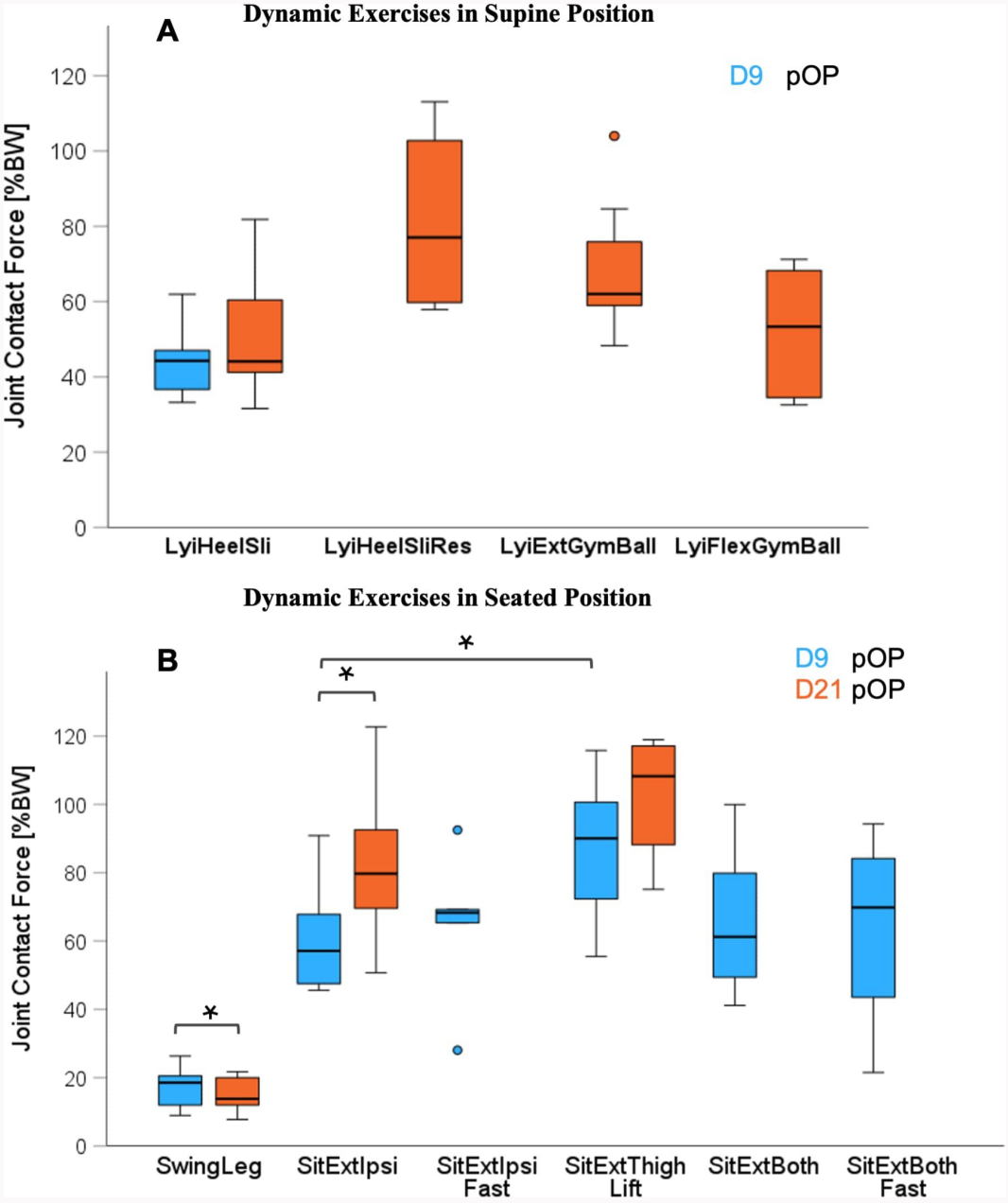

Fig. 4

Change of maximum resultant contact force (Fres max) in the group of dynamic exercises on day 9 (D9) compared with day 21 (D21). *p ≤ 0.05. BW, body weight; D, day; LyiExtGymBall, supine position with straight legs and ankle on a gymnastic ball (65 cm) with pressure in the direction of the ball; LyiFlexGymBall, supine position with bent legs and ankle on a gymnastic ball (65 cm) with pressure in the direction of the ball; LyiHeelSli, lying with sliding heel on the bench from knee extension to maximum flexion and including dorsal extension; LyiHeelSliRes, variation: additional resistance on the lower leg by the therapist; pOP, postoperative; SitExtIpsi, sitting and bring ipsilateral leg into maximum extension.

(95% CI 11.3 to 18.7) on day 21, although this was not statistically significant (Figure 2d).

- Lying heel slides showed $F_{res\ max}$ values of 44% BW (95% CI 38.1 to 49.9) on day nine and 50% BW (95% CI 40.2 to 59.8) on day 21. When performed with additional resistance, $F_{res\ max}$ increased to 81% BW (95% CI 58.5 to 103.5), showing a trend towards an increase (p = 0.068) (Figure 2d).

Crutch-assisted gait and stair climbing

- Three-point gait exhibited two load peaks: $F_{res\ max\ 1}$ = 155% BW (95% CI 134.3 to 175.7) and $F_{res\ max\ 2}$ = 120% BW (95% CI 103 to 137) on day nine, increasing to 178% BW and 194% BW on day 21 (Figure 2f).
- Four-point gait resulted in a significant 48% increase in $F_{res\ max\ 2}$ from day nine to day 21 (p = 0.018), indicating greater joint loading compared to three-point gait (Figure 2f).
- Stair ascent exhibited the highest knee joint loads, with $F_{res\ max}$ increasing significantly from 177% BW (95% CI 156.3 to 197.7) on day nine to 193% BW (95% CI 176.7 to 209.3) on day 21.
- Stair descent exhibited similarly high forces, with significant increases for both peaks compared to day nine, reinforcing the demand these activities place on the knee joint during early rehabilitation (Figure 2f).

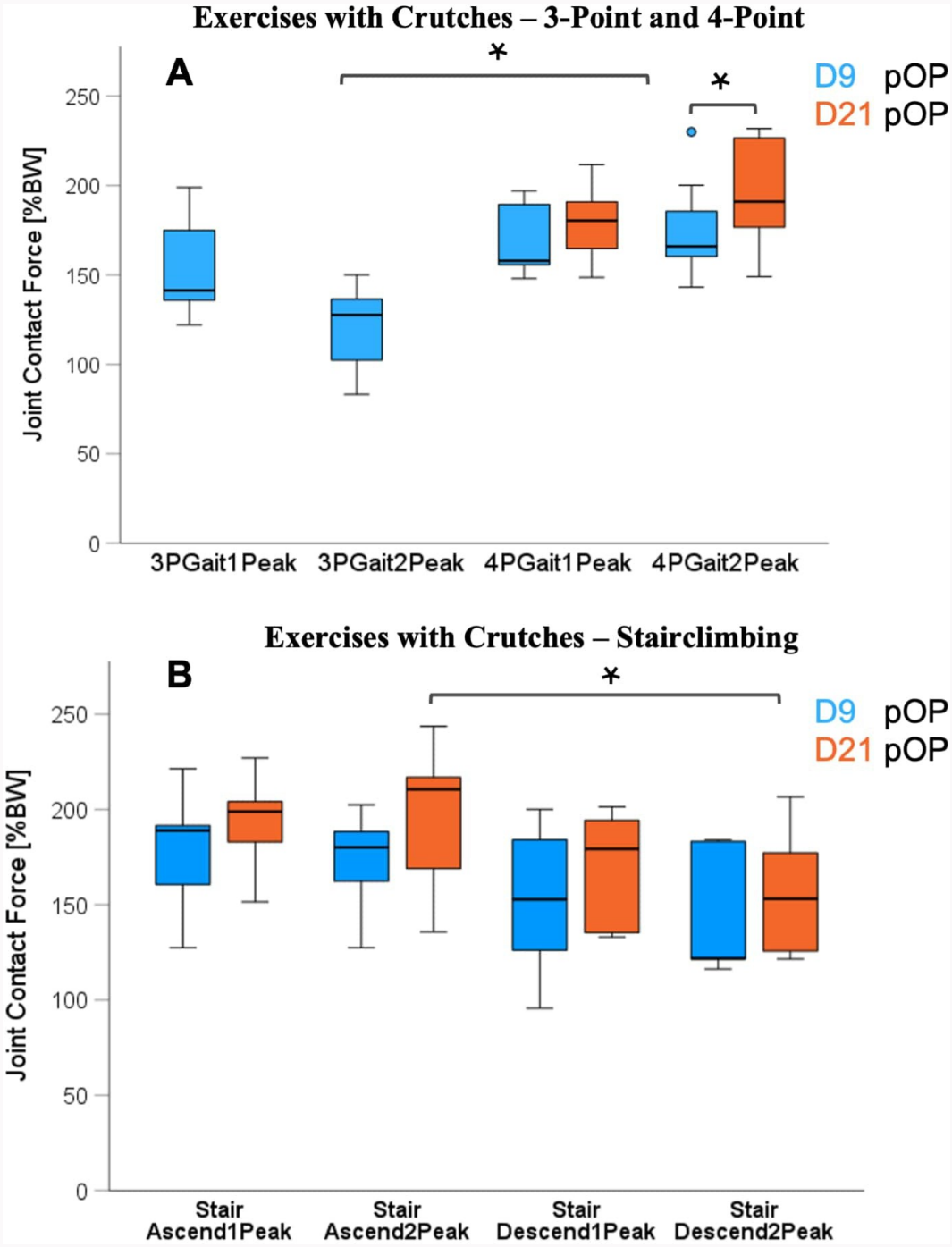

Fig. 5
Change of maximum resultant contact force (Fres max) in the group of exercises with crutches on day 9 (D9) compared with day 21 (D21). *p ≤ 0.05. BW, body weight; D, day; P, point; pOP, postoperative.

Changes in the in vivo knee joint loads during the first three weeks postoperatively

- No significant changes in relaxed lying exercises were observed, but a minor decrease in relaxed sitting loads was noted (Figure 3a).
- $F_{res\ max}$ during isometric knee extension significantly increased by 28% from day nine to day 21 ($p = 0.025$), emphasizing the impact of progressive resistance training (Figure 3c).
- A trend towards increased loads was noted for hip abduction and adduction exercises, but statistical significance was not reached ($p = 0.068$).
- Dynamic seated knee extension exhibited a significant 34% increase in $F_{res\ max}$ from day nine to day 21 ($p = 0.018$), underlining the progressive adaptation in joint loading (Figure 4b).
- In crutch-assisted walking, a trend towards increased contact forces was observed in four-point gait ($p = 0.086$), with a significant 11% increase in $F_{res\ max\ 2}$ ($p = 0.015$) (Figure 5a).

- Stair ascent and descent showed the highest knee joint loads across all exercises, with stair climbing exhibiting an upward trend in load intensity between day nine and day 21, though not all changes were statistically significant (Figure 5b).

Discussion

Within this study, exercises in a relaxed state showed the lowest knee joint contact loads, while body weightbearing activities showed the highest. Climbing stairs with crutches caused higher contact forces compared to other exercises, but these loads were still below those measured during level walking a few months postoperatively.[12] Joint contact forces during level walking were reported by Kutzner et al[12] at 261% BW and used as a reference. Passive exercises, such as stretching the knee in a relaxed lying position, showed comparatively low contact forces. When patients contracted the muscle in extension, contact forces increased, illustrating the impact of muscle contraction, particularly the quadriceps femoris, on joint forces.[11,16] These loads significantly increased within the first three weeks postoperatively (+28%), likely due to reduced pain and increased consistency in exercise performance, as well as regained quadriceps strength and higher periarticular muscle co-contraction.[35-37] Kutzner et al[12] demonstrated the impact of muscle co-contractions by measuring in vivo knee loads during one-leg stance instability, observing loads over 550% BW. By measuring the axial forces acting on the tibiofemoral joint, D'Lima et al[10] found that increasing muscle strength during postoperative healing increased joint forces, such as during stair climbing.

Isometric muscle contraction exercises showed increased in vivo forces with added resistance from the therapist, particularly during hip joint abduction. Despite this, the use of, for example resistance bands, can promote muscle hypertrophy and is easily accessible to patients, as long as forces do not exceed harmful limits.[38,39] Overall, relaxed and swelling reducing exercises showed lower loads in sitting positions compared to supine positions. When contracting the muscles, joint partners are pressed together and thus increase the contact force.[40,41] The highest impact is exerted by the quadriceps femoris, which has the greatest force effect during extension,[42] explaining why exercises in extension led to higher maximum contact forces than in flexion.

To reduce joint loading after TKA or osteosynthesis, crutches are commonly used. This study found that a three-point gait was more effective in reducing in vivo contact forces compared to a four-point gait, as also shown for hip implants by Damm et al,[43] however a four-point gait allowed for a more physiological gait pattern.[44] Fregly et al[45] found that walking sticks reduced tibiofemoral contact forces by 10% to 39% compared to normal walking. When comparing crutch-assisted exercises in this study to previously published level walking measurements, contact loads were considerably lower.[12,13] Loads of 261% BW during level walking, 316% BW during stair ascent, and 346% BW during stair descent were measured seven to 22 months postoperatively.[12] Joint contact loads during four-point walking showed a trend to increase from day nine to day 21, but remained 26% lower than Kutzner et al's[12] 2010 data. Our data support the recommendation of three-point gait in the starting phase of rehabilitation due to its reduced peak loads. However, patients can easily be recommended to transition to four-point gait in the further course of healing, as it better simulates normal walking and has only minor clinical differences from the three-point gait.

Stair ascent and descent resulted in substantially higher loads than all other investigated exercises. Individual contact forces of up to 244% BW were observed on day nine, making stair climbing the highest load exercise studied. For all crutch-assisted exercises, contact forces increased from day nine to day 21. Despite this, stair climbing with crutches showed reduced contact forces compared to level walking or stair climbing at later postoperative timepoints.[12,19] Climbing stairs is essential for ADL, and inability often requires assistance, significantly impacting quality of life.[46,47] While crutches do not reduce joint loads as much as surgeons may intend,[43] they can provide walking safety for patients with insufficient leg strength postoperatively. Proper training with crutches must be supervised by a physiotherapist to prevent additional loading from incorrect handling.[48,49] Ideally, this should be carried out preoperatively.[50,51]

Our study results provide valuable insights into the stress on knee joints during early postoperative physiotherapy and help to optimize rehabilitation protocols. Although immediate full weightbearing is now the standard procedure for patients undergoing primary knee arthroplasty, our findings provide valuable insights into knee joint loading that can inform rehabilitation strategies for other knee-related surgical procedures. These include periarticular fractures, revisions of knee arthroplasties, and periprosthetic fractures, where optimal weightbearing guidelines remain less defined. The data presented in this study can serve as a reference for postoperative physiotherapy planning, aiding clinicians in tailoring rehabilitation protocols to specific patient needs.

Based on the results of this study, the following recommendations for physiotherapists and physicians should be considered. Relaxed exercises, such as sitting and lying down without muscle contractions, offer the least stress and are ideal as a base position for the start of rehabilitation. Swelling reduction exercises such as dorsiflexion and plantar flexion while lying down should be incorporated, especially in a seated position. Isometric exercises while lying down, such as extension with careful resistance, promote the muscular strength of the quadriceps femoris muscle. Dynamic seated exercises, such as leg swings and extensions, provide moderate loads and can improve joint functionality. These exercises are especially beneficial when weightbearing is restricted or for patient-specific reasons, as they reduce joint forces while still offering effective muscle training.

Exercises with crutches, in particular the three-point gait, effectively reduce joint loads and should be used early on to promote mobility, as should climbing stairs with crutches to promote everyday mobility. In general, early full weightbearing should be encouraged in order to speed up rehabilitation and shorten hospital stays. Intensive physiotherapy and targeted muscle strengthening are crucial for reducing postoperative complications and achieving functional milestones more quickly.

Central to our analysis was that, except for body weight exercises, all exercises studied were below the loads from level walking post-recovery, indicating that these exercises can be performed safely in postoperative rehabilitation to regain function and strength.

Despite being the first of its kind, our study has limitations. The small sample size of nine patients and exclusive investigation of cruciate-retaining implants limits the generalizability of the results. Individual differences in age, weight, and preoperative health status could influence the results. Additionally, the potential impact of postoperative pain and analgesic medication on exercise performance and joint loading was not assessed, introducing further variability. Furthermore, not every patient performed each exercise. Resistance applied by the physical therapist was not measured, compromising exact quantitative statements about the correlating effects of counterforce during physiotherapy.

Nonetheless, this study provides for the first time realistic in vivo loading data during physiotherapy exercises in the early postoperative period of rehabilitation after knee surgery. The study can aid surgeons and therapists in individualized recommendations and establish a more research-based treatment regimen.

Supplementary material

Definitions of gait patterns.

References

1. **Price AJ**, **Alvand A**, **Troelsen A**, **et al**. Knee replacement. *Lancet*. 2018;392(10158):1672–1682.
2. **Bourne RB**, **Chesworth BM**, **Davis AM**, **Mahomed NN**, **Charron KDJ**. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? *Clin Orthop Relat Res*. 2010;468(1):57–63.
3. **Dávila Castrodad IM**, **Recai TM**, **Abraham MM**, **et al**. Rehabilitation protocols following total knee arthroplasty: a review of study designs and outcome measures. *Ann Transl Med*. 2019;7(Suppl 7):S255.
4. **Artz N**, **Elvers KT**, **Lowe CM**, **Sackley C**, **Jepson P**, **Beswick AD**. Effectiveness of physiotherapy exercise following total knee replacement: systematic review and meta-analysis. *BMC Musculoskelet Disord*. 2015;16:15.
5. **Munin MC**, **Rudy TE**, **Glynn NW**, **Crossett LS**, **Rubash HE**. Early inpatient rehabilitation after elective hip and knee arthroplasty. *JAMA*. 1998;279(11):847–852.
6. **Hol AM**, **van Grinsven S**, **Lucas C**, **van Susante JLC**, **van Loon CJM**. Partial versus unrestricted weight bearing after an uncemented femoral stem in total hip arthroplasty: recommendation of a concise rehabilitation protocol from a systematic review of the literature. *Arch Orthop Trauma Surg*. 2010;130(4):547–555.
7. **Jöllenbeck T**, **Schönle C**. Die Teilbelastung nach Knie- oder Hüft-Totalendoprothese: Unmöglichkeit der Einhaltung, ihre Ursachen und Abhilfen [Partial load after knee and hip total endoprosthesis: impossibility of observing their causes and remedies]. *Z Orthop Ihre Grenzgeb*. 2005;143(2):124–128. . [Article in German].
8. **Heisel J**. Rehabilitation nach endoprothetischem Ersatz von Hüfte und Knie [Rehabilitation following total hip and knee replacement]. *Orthopäde*. 2008;37(12):1217–1232. . [Article in German].
9. **Schmidt J**, **Riedel T**, **Grundler S**. Nachbehandlungsempfehlungen 2024: Deutsche Gesellschaft für Unfallchirurgie (DGU). 2024. https://www.dgu-online.de/fileadmin/dgou/dgou/Dokumente/Gremien/Sektionen/Rehabilitation/NBE_2024_web.pdf (date last accessed 15 August 2025).
10. **D'Lima DD**, **Patil S**, **Steklov N**, **Slamin JE**, **Colwell CW Jr**. Tibial forces measured in vivo after total knee arthroplasty. *J Arthroplasty*. 2006;21(2):255–262.
11. **Bergmann G**, **Bender A**, **Graichen F**, **et al**. Standardized loads acting in knee implants. *PLoS One*. 2014;9(1):e86035.
12. **Kutzner I**, **Heinlein B**, **Graichen F**, **et al**. Loading of the knee joint during activities of daily living measured in vivo in five subjects. *J Biomech*. 2010;43(11):2164–2173.
13. **Damm P**, **Kutzner I**, **Bergmann G**, **Rohlmann A**, **Schmidt H**. Comparison of in vivo measured loads in knee, hip and spinal implants during level walking. *J Biomech*. 2017;51:128–132.
14. **Heinlein B**, **Kutzner I**, **Graichen F**, **et al**. ESB Clinical Biomechanics Award 2008: complete data of total knee replacement loading for level walking and stair climbing measured in vivo with a follow-up of 6-10 months. *Clin Biomech (Bristol)*. 2009;24(4):315–326.
15. **D'Lima DD**, **Patil S**, **Steklov N**, **Slamin JE**, **Colwell CW Jr**. The Chitranjan Ranawat Award: in vivo knee forces after total knee arthroplasty. *Clin Orthop Relat Res*. 2005;440:45–49.
16. **Trepczynski A**, **Kutzner I**, **Schwachmeyer V**, **Heller MO**, **Pfitzner T**, **Duda GN**. Impact of antagonistic muscle co-contraction on in vivo knee contact forces. *J Neuroeng Rehabil*. 2018;15(1):101.
17. **Damm P**, **Brackertz S**, **Streitparth F**, **et al**. ESB Clinical Biomechanics Award 2018: muscle atrophy-related increased joint loading after total hip arthroplasty and their postoperative change from 3 to 50 months. *Clin Biomech (Bristol)*. 2019;65:105–109.
18. **Damm P**, **Zonneveld J**, **Brackertz S**, **Streitparth F**, **Winkler T**. Gluteal muscle damage leads to higher in vivo hip joint loads 3 months after total hip arthroplasty. *PLoS One*. 2018;13(1):e0190626.
19. **Winkler T**, **Bell L**, **Bender A**, **et al**. Periarticular muscle status affects *in vivo* tibio-femoral joint loads after total knee arthroplasty. *Front Bioeng Biotechnol*. 2023;11:1075357.
20. **Kutzner I**, **Heinlein B**, **Graichen F**, **et al**. Loading of the knee joint during ergometer cycling: telemetric in vivo data. *J Orthop Sports Phys Ther*. 2012;42(12):1032–1038.
21. **Bergmann G**, **Kutzner I**, **Bender A**, **et al**. Loading of the hip and knee joints during whole body vibration training. *PLoS One*. 2018;-13(12):e0207014.
22. **D'Lima DD**, **Steklov N**, **Fregly BJ**, **Banks SA**, **Colwell CW Jr**. In vivo contact stresses during activities of daily living after knee arthroplasty. *J Orthop Res*. 2008;26(12):1549–1555.
23. **Damm P**, **Reitmaier S**, **Hahn S**, **Waldheim V**, **Firouzabadi A**, **Schmidt H**. In vivo hip and lumbar spine implant loads during activities in forward bent postures. *J Biomech*. 2020;102:109517.
24. **Mündermann A**, **Dyrby CO**, **D'Lima DD**, **Colwell CW**, **Andriacchi TP**. In vivo knee loading characteristics during activities of daily living as measured by an instrumented total knee replacement. *J Orthop Res*. 2008;26(9):1167–1172.
25. **Prince JM**, **Bernatz JT**, **Binkley N**, **Abdel MP**, **Anderson PA**. Changes in femoral bone mineral density after total knee arthroplasty: a systematic review and meta-analysis. *Arch Osteoporos*. 2019;14(1):23.
26. **Heesterbeek PJC**, **Wymenga AB**, **van Hellemondt GG**. No difference in implant micromotion between hybrid fixation and fully cemented revision total knee arthroplasty: a randomized controlled trial with radiostereometric analysis of patients with mild-to-moderate bone loss. *J Bone Joint Surg Am*. 2016;98-A(16):1359–1369.
27. **Jones RE**, **Russell RD**, **Huo MH**. Wound healing in total joint replacement. *Bone Joint J*. 2013;95-B(11 Suppl A):144–147.
28. **L Snell D**, **Hipango J**, **Sinnott KA**, **et al**. Rehabilitation after total joint replacement: a scoping study. *Disabil Rehabil*. 2018;40(14):1718–1731.
29. **Youm T**, **Maurer SG**, **Stuchin SA**. Postoperative management after total hip and knee arthroplasty. *J Arthroplasty*. 2005;20(3):322–324.
30. **Sheth NP**, **Foran JRH**. Total knee replacement exercise guide. American Academy of Orthopaedic Surgeons. 2022. https://orthoinfo.aaos.org/en/recovery/total-knee-replacement-exercise-guide (date last accessed 15 August 2025).
31. **Schwachmeyer V**, **Kutzner I**, **Bornschein J**, **Bender A**, **Dymke J**, **Bergmann G**. Medial and lateral foot loading and its effect on knee joint loading. *Clin Biomech (Bristol)*. 2015;30(8):860–866.
32. **Heinlein B**, **Graichen F**, **Bender A**, **Rohlmann A**, **Bergmann G**. Design, calibration and pre-clinical testing of an instrumented tibial tray. *J Biomech*. 2007;40 Suppl 1:S4–10.
33. **Graichen F**, **Arnold R**, **Rohlmann A**, **Bergmann G**. Implantable 9-channel telemetry system for in vivo load measurements with orthopedic implants. *IEEE Trans Biomed Eng*. 2007;54(2):253–261.
34. **Bender A**, **Bergmann G**. Determination of typical patterns from strongly varying signals. *Comput Methods Biomech Biomed Engin*. 2012;15(7):761–769.
35. **Palmieri-Smith RM**, **Villwock M**, **Downie B**, **Hecht G**, **Zernicke R**. Pain and effusion and quadriceps activation and strength. *J Athl Train*. 2013;48(2):186–191.

36. **Mizner RL**, **Petterson SC**, **Snyder-Mackler L**. Quadriceps strength and the time course of functional recovery after total knee arthroplasty. *J Orthop Sports Phys Ther*. 2005;35(7):424–436.
37. **Moon YW**, **Kim HJ**, **Ahn HS**, **Lee DH**. Serial changes of quadriceps and hamstring muscle strength following total knee arthroplasty: a meta-analysis. *PLoS One*. 2016;11(2):e0148193.
38. **Lopes JSS**, **Machado AF**, **Micheletti JK**, **de Almeida AC**, **Cavina AP**, **Pastre CM**. Effects of training with elastic resistance versus conventional resistance on muscular strength: a systematic review and meta-analysis. *SAGE Open Med*. 2019;7:2050312119831116.
39. **Kim M**, **Kuruma H**, **Thawisuk C**. Effectiveness of elongation band exercise on the upper limb strength and range of motion among older adults. *J Exerc Rehabil*. 2022;18(2):110–116.
40. **Bergschmidt P**, **Darowski M**, **Bonacker J**, **Leubert N**, **Kebbach M**, **Mittelmeier W**. Biomechanik des endoprothetisch versorgten Kniegelenks. In: Perka C, Heller K-D, eds. *AE-Manual Der Endoprothetik*. Berlin, Heidelberg: Springer, 2020: 1–23.
41. **Kummer B**. *Biomechanik: Form Und Funktion Des Bewegungsapparates*. Cologne, Germany: Deutscher Ärzte-Verlag, 2004.
42. **Michael Schünke ES**, **Schumacher U**. *PROMETHEUS Allgemeine Anatomie Und Bewegungssystem*. Georg Thieme Verlag KG, 2014: 442–453.
43. **Damm P**, **Schwachmeyer V**, **Dymke J**, **Bender A**, **Bergmann G**. In vivo hip joint loads during three methods of walking with forearm crutches. *Clin Biomech (Bristol)*. 2013;28(5):530–535.
44. **McDonough AL**, **Razza-Doherty M**. Some biomechanical aspects of crutch and cane walking: the relationship between forward rate of progression, symmetry, and efficiency--a case report. *Clin Podiatr Med Surg*. 1988;5(3):677–693.
45. **Fregly BJ**, **D'Lima DD**, **Colwell CW Jr**. Effective gait patterns for offloading the medial compartment of the knee. *J Orthop Res*. 2009; 27(8):1016–1021.
46. **Gavin JP**, **Immins T**, **Wainwright T**. Stair negotiation as a rehabilitation intervention for enhancing recovery following total hip and knee replacement surgery. *Int J Orthop Trauma Nurs*. 2017;25:3–10.
47. **Costigan PA**, **Deluzio KJ**, **Wyss UP**. Knee and hip kinetics during normal stair climbing. *Gait Posture*. 2002;16(1):31–37.
48. **Watanabe M**, **Tani H**. Using crutches during walking possibly reduces gait imagery accuracy among healthy young and older adults. *J Phys Ther Sci*. 2022;34(10):673–677.
49. **Manocha RHK**, **MacGillivray MK**, **Eshraghi M**, **Sawatzky BJ**. Injuries associated with crutch use: a narrative review. *PM R*. 2021;13(10):1176–1192.
50. **Beaupre LA**, **Lier D**, **Davies DM**, **Johnston DBC**. The effect of a preoperative exercise and education program on functional recovery, health related quality of life, and health service utilization following primary total knee arthroplasty. *J Rheumatol*. 2004;31(6):1166–1173.
51. **Vukomanović A**, **Popović Z**, **Durović A**, **Krstić L**. The effects of short-term preoperative physical therapy and education on early functional recovery of patients younger than 70 undergoing total hip arthroplasty. *Vojnosanit Pregl*. 2008;65(4):291–297.

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Data sharing

Selected trials of each investigated subject and trial can be downloaded at the public data base https://orthoload.com/

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Ethical review statement

The in vivo studies were approved by the Ethics Committee of the Charité – Universitätsmedizin Berlin (EA2/057/09) and registered at the 'German Clinical Trials Register' (DRKS00000563). All participants gave written informed consent before data collection began.

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