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Review

Inter-limb kinetic asymmetries during sit-to-stand performance persist following unilateral total knee arthroplasty: A systematic review and meta-analysis

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ABSTRACT

Background: Kinetic asymmetries during sit-to-stand have been consistently observed early after total knee arthroplasty; however, the longer-term outcomes are less clear. The purpose of this systematic review and meta-analysis was to analyze the results of studies examining inter-limb kinetic symmetry during sit-to-stand performance among individuals who were at least one-year post unilateral total knee arthroplasty.
Methods: PubMed, SPORTDiscus, CINAHL, and Health Source databases were searched. Studies were included if they were published in a peer-reviewed journal, included subjects who had undergone unilateral total knee arthroplasty at least one-year prior, and examined vertical ground reaction forces and/or knee extension moments for the involved and uninvolved limbs during sit-to-stand performance. Data were transformed into a limb symmetry index, which expressed the ratio of the peak forces/moments for the involved limb, relative to the uninvolved limb (1.0 reflects perfect symmetry). These ratios were meta-analyzed using the ratio of means method.
Findings: Seven studies were deemed eligible for inclusion. Ground reaction force data was pooled from seven studies and knee extension moment data was pooled from two studies. For the peak vertical ground reaction forces, the pooled limb symmetry index was 0.96 ($CI_{95\%}$ = [0.93, 0.99]). For the peak knee extension moments, the pooled limb symmetry index was 0.91 ($CI_{95\%}$ = [0.84, 0.98]). In both cases this reflects greater limb/knee loading for the uninvolved limb, relative to the involved limb.
Interpretation: Asymmetries in limb/knee loading persist beyond the one-year post-operative period following total knee arthroplasty, potentially contributing to degenerative changes for the uninvolved limb.

1. Introduction

Knee osteoarthritis (OA) is a very common musculoskeletal condition (Zhang and Jordan, 2010), with over 10% of adults 60 years of age or older reporting symptomatic knee OA (Dillon et al., 2006). Total knee arthroplasty (TKA) is typically recommended for individuals with end-stage knee OA who have tried conservative treatment, but are still experiencing symptoms that negatively impact their daily function (Quinn et al., 2017). Over 700,000 TKAs are performed each year in the United States alone (Price et al., 2018) and this number is expected to increase in the coming years (Singh et al., 2019). Most patients report improved symptoms following TKA, even within the first few months after surgery (Boonstra et al., 2010; Skou et al., 2016). However, individuals who have undergone TKA exhibit persistent deficits in lower body function compared to age-matched controls (Bade et al., 2010; Bonnefoy-Mazure et al., 2017; Boonstra et al., 2008; Sayah et al., 2021),

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with as many as 20% of patients expressing dissatisfaction with their long-term outcomes following TKA, often due to unresolved functional limitations (Ayers et al., 2022; Gunaratne et al., 2017). Developing a better understanding of the typical time course of neuromuscular recovery following TKA could help to guide rehabilitation strategies to promote improved long-term outcomes.

Previous studies have found that individuals who have undergone TKA demonstrate altered lower body kinetics within the first 3–4 months after surgery (Christiansen et al., 2013; Farquhar et al., 2008; Mizner and Snyder-Mackler, 2005; Pua et al., 2022; Van Onsem et al., 2020; Worsley et al., 2013; Zeni Jr et al., 2013). More specifically, they tend to offload their involved limb, placing greater load on their uninvolved limb, when performing double-leg dynamic tasks, such as standing from a sitting position (sit-to-stand). For example, Mizner and Snyder-Mackler (2005) analyzed sit-to-stand performance in individuals who had undergone TKA 3 months prior and found that, on average, peak vertical ground reaction forces (vGRFs) were 14% lower for the involved limb compared to the uninvolved limb. They also found that peak internal knee extension moments were lower for the involved limb (vs. the uninvolved limb).

To some extent, asymmetrical limb loading is to be expected during the early post-operative time frame, as individuals often exhibit deficits in quadriceps strength and/or activation, knee motion, and/or pain at this point in the recovery process (Christiansen et al., 2013; Mizner and Snyder-Mackler, 2005; Pua et al., 2022; Van Onsem et al., 2020). However, secondary musculoskeletal problems could arise if these altered lower body kinetic patterns persist. For example, the tendency to shift load away from the involved limb, toward the uninvolved limb, during routine functional tasks such as sit-to-stand could potentially contribute to degenerative changes for the uninvolved limb (Alnahdi et al., 2016; Sayeed et al., 2011; Shakoor et al., 2002; Shao et al., 2013). In addition, previous studies have found that greater inter-limb kinetic asymmetry during sit-to-stand is associated with poorer function following TKA (Christiansen et al., 2011; Pua et al., 2022; Van Onsem et al., 2020). Finally, it should be noted that chronic underloading of the involved limb could perpetuate or even worsen neuromuscular deficits for the involved limb, contributing to further decrements in lower body function (Pua et al., 2022). This is particularly true for a task such as sit-to-stand, which is performed frequently throughout the day (on average, 60 times per day) (Dall and Kerr, 2010) and imposes high demands on the lower body compared to other functional tasks such as walking, as sit-to-stand involves large ranges of motion and relatively high hip and knee extension moments during the rising phase (Li et al., 2021; Myles et al., 2002; Roebroeck et al., 1994).

While it appears that individuals tend to exhibit inter-limb asymmetry in lower body loading early after TKA (i.e. within the first 6 months), the longer-term residual effects of TKA on inter-limb kinetic symmetry are less clear. For instance, Alnahdi et al. (2016) reported that individuals who had undergone TKA one year prior demonstrated lower peak vGRFs and peak knee extension moments for their involved limb vs. their uninvolved limb during sit-to-stand performance, which suggests that inter-limb kinetic asymmetries tend to persist beyond the early post-operative period. However, in contrast, Farquhar et al. (2008) reported that peak vGRFs and peak knee extension moments during sit-to-stand were not significantly different for the involved and uninvolved limbs at the one-year post-operative time point. Combining the results of studies examining inter-limb kinetic symmetry at an extended post-operative period (one or more years post-TKA) could help to resolve this discrepancy in the literature. To our knowledge, there has not been an attempt to perform a meta-analysis to combine the results of studies examining inter-limb kinetic symmetry during sit-to-stand following TKA (either in the short- or longer-term post-operative period). Resolving this discrepancy in the literature could help us better understand how persistent kinetic asymmetries may impact long-term outcomes following TKA and provide insights that could inform rehabilitation. Specifically, establishing a consensus regarding inter-limb symmetry across the literature could help practitioners identify targets throughout rehabilitation and serve as a benchmark to examine future associations between inter-limb symmetry and long-term complications following TKA. Therefore, the purpose of this systematic review and meta-analysis was to analyze the results of previous studies examining inter-limb kinetic symmetry during sit-to-stand performance among individuals who were at least one-year post unilateral TKA.

2. Methods

2.1. Eligibility criteria

This systematic review and meta-analysis was conducted in accordance with the "Preferred Reporting Items for Systematic Reviews and Meta-Analysis" (PRISMA) guidelines (Page et al., 2021). Studies were included in this review if they were published in a peer-reviewed journal, included subjects who had undergone unilateral TKA (regardless of prosthetic design) at least one-year prior, and examined vGRFs and/or sagittal plane knee moments (internal knee extension moments) for the involved and uninvolved limbs during sit-to-stand performance. We did not examine anterior-posterior or medial-lateral ground reaction forces, since the vGRF tends to be the main contributor to upward body motion during a sit-to-stand task (Hirschfeld et al., 1999). We considered examining inter-limb symmetry for kinematic variables, such as knee flexion angles; however, we opted to focus on limb/joint kinetics, since elevated joint loading is thought to be more directly linked to the development of secondary musculoskeletal conditions such as osteoarthritis (Felson, 2013; Griffin and Guilak, 2005). Sit-to-stand (or "chair rising") was selected as the task of interest since it is a relatively demanding functional task that involves distributing weight between the limbs, allowing individuals to potentially compensate more by offloading their involved limb, compared to other functional tasks such as walking and stair ascent/descent, which involve periods of single-limb support (Zeni Jr et al., 2013). There is also evidence that the degree of inter-limb asymmetry during sit-to-stand is related to function in individuals who have undergone TKA (Christiansen et al., 2011; Pua et al., 2022; Van Onsem et al., 2020). Finally, sit-to-stand is a task that is very commonly analyzed in studies examining biomechanics following TKA. The one-year cutoff point was selected since this is well beyond the usual post-operative rehabilitation period (typically 2–3 months) and, as a result, study participants were likely to have completed any type of formal post-operative rehabilitation. In some cases, investigators only reported the average time post-surgery for their entire sample. In these cases, studies were included if the average time post-surgery was at least 12 months. Only peer-reviewed journal articles were eligible for inclusion; conference abstracts and dissertations were not included. Studies were excluded if their sample included patients who underwent bilateral TKA, had previously undergone joint arthroplasty for their uninvolved limb, or underwent TKA revision.

2.2. Search strategy

Database searches of PubMed, SPORTDiscus, CINAHL, and Health Source were performed in November of 2022 using the following keyword combination: (knee arthroplasty OR TKA OR knee replacement) AND (biomechanics OR kinetics OR loading OR weight-bearing) AND (sit-to-stand OR chair rise OR chair rising). Once duplicate results were removed, two investigators independently reviewed article titles to evaluate potential relevance and then reviewed abstracts for articles that were deemed potentially relevant based on their title ("titles-first" approach) (Mateen et al., 2013). The articles identified during this initial screening were independently read in-full by the same two investigators to determine their eligibility. Any discrepancies during this search and screen process were resolved by a third independent reviewer. The reference lists of articles identified during the literature search were also reviewed in order to identify additional potentially relevant articles (Wright et al., 2007). The reference lists of two systematic reviews (Komnik et al., 2015; Wang et al., 2019) related to the topic of lower body biomechanics following TKA were also reviewed for the same purpose.

A flow diagram was used to depict the number of studies identified and included/excluded at each stage of the search and screening process, as well as the reasons for exclusion. The structure of this flow diagram was based on the PRISMA flow diagram (Page et al., 2021).

2.3. Data extraction and quality assessment

For articles deemed eligible for review, data were extracted and added to a spreadsheet. The data extracted included key sample characteristics (male/female distribution, age, height, weight, body mass index, time post-TKA), sit-to-stand task details, and relevant dependent variables of interest.

A modified version of the Appraisal tool for Cross-Sectional Studies (AXIS) was used to appraise the methodological quality and risk of bias associated with the studies included in this review (Downes et al., 2016). The original AXIS tool includes 20 questions. The tool was modified by removing questions 7, 13, and 14 because of their limited relevance to our research question. In addition, question 19 was revised so that a "yes" answer corresponded with better quality and less risk of bias (consistent with the other AXIS tool questions). These modifications to the AXIS tool are consistent with those proposed by Bagordo et al. (2020). The modified version of the AXIS tool included 17 total questions (re-numbered 1–17), with higher scores reflecting better methodological quality and less risk of bias. Two investigators independently scored articles using the modified AXIS tool. Questions answered "yes" received a score of 1, questions answered "no" or "unable to determine" received a score of 0. Discrepancies in scoring were discussed by the investigators so that a consensus could be reached. Table 1 includes the questions included in the modified AXIS tool. While there is no universally accepted cutoff, a score of at least 12 out of 17 was considered to represent "good" quality for the modified AXIS tool (Bagordo et al., 2020).

2.4. Quantitative analysis

In some cases, investigators reported separate means for each limb, while in other cases they reported limb loading as a ratio (e.g. involved limb/uninvolved limb). In order to combine results from multiple studies, data were transformed into a limb symmetry index (LSI), which expressed the ratio of the peak forces/moments for the involved limb, relative to the uninvolved limb (Eq. (1)). An LSI of 1.0 reflects perfect inter-limb symmetry, an LSI <1.0 reflects greater loading for the uninvolved limb, and an LSI >1.0 reflects greater loading for the involved limb. We opted to express limb loading as a ratio, since this was the most common approach used among the papers included in this review.

$$\mathrm{LSI} = \frac{\text{Involved limb loading}}{\text{Uninvolved limb loading.}} \quad (1)$$

Boonstra et al. (2010) and Farquhar et al. (2008) only presented their results in figures. Numerical values were extracted from these figures using WebPlotDigitizer software (automeris.io/WebPlotDigitizer/) so their results could be analyzed. The authors did not specify whether the error bars presented in their figures represented standard deviations or standard errors. Reproducing the p-values for the differences between groups provided in each of these studies, we found that assuming the error bars were standard deviations for Boonstra et al. (2010) and standard errors for Farquhar et al. (2008) most closely reproduced the p-values for the differences between groups provided in these two papers. However, when pooling the results of these studies for our meta-analysis, we also conducted sensitivity analyses assuming the opposite (i.e. that the error bars represented standard errors for Boonstra et al., 2010 and standard deviations for Farquhar et al., 2008). None of these sensitivity analyses significantly changed any of the pooled outcomes.

LSI ratios for the peak vGRFs and peak knee extension moments were meta-analyzed using the ratio of means method (Friedrich et al., 2008). Meta-analyses were performed on the logarithmic scale using the generic inverse variance method in Review Manager (RevMan version 5.4; Cochrane Collaboration, Oxford, UK) before being converted back to the absolute scale, as previously described by Friedrich et al. (2011). For studies that provided means and standard deviations for the

Table 1
Answers to the modified AXIS tool questions for the studies included in this review.

Article	Questions																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
Alnahdi et al. (2016)	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	15
Bakirhan et al. (2012)	1	1	0	1	0	0	1	1	1	0	1	1	1	1	0	1	1	12
Boonstra et al. (2008)	0	1	0	1	1	0	1	1	1	1	1	0	1	1	1	0	1	12
Boonstra et al. (2010)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	16
Chu et al. (2013)	0	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	14
Farquhar et al. (2008)	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	0	1	14
van der Ven et al. (2017)	1	1	1	1	1	1	1	0	1	0	1	1	1	1	0	1	1	14

Responses to the modified AXIS tool questions (listed below) for each study included in this review; 1 indicates a "yes" response, 0 indicates a "no" or "unable to determine" response; the last column is the total
Question 1 – were the aims of the study clear?
Question 2 – was the study design appropriate for the stated aim(s)?
Question 3 – was the sample size justified?
Question 4 – was the target population clearly defined?
Question 5 – was the sample taken from an appropriate population base so that it closely represented the target population under investigation?
Question 6 – was the selection process likely to select subjects that were representative of the target population under investigation?
Question 7 – were the risk factor and outcome variables measured appropriate to the aims of the study?
Question 8 – were the risk factor and outcome variables measured correctly using the instruments/measurements that had been trialed, piloted, or published previously?
Question 9 – is it clear what was used to determine statistical significance and/or precision estimates?
Question 10 – were the methods sufficiently described to enable them to be repeated?
Question 11 – were the basic data adequately described?
Question 12 – were the results internally consistent?
Question 13 – were the results presented for all the analyses described in the methods?
Question 14 – were the authors' discussions and conclusions justified by the results?
Question 15 – were the limitations of the study discussed?
Question 16 – was the study free of any funding sources or conflicts of interest that may affect the authors' interpretation of the results?
Question 17 – was ethical approval and consent of participants attained?

involved and uninvolved limbs, ratios and standard errors were calculated on the logarithmic scale, whereas for studies that reported ratios with standard deviations, the ratio and its standard error were converted to the logarithmic scale. Random effects models, which incorporate between-trial heterogeneity and give wider and more conservative confidence intervals (CI) when heterogeneity is present, were used for all pooled analyses (DerSimonian and Laird, 1986). Statistical heterogeneity was assessed using the I^2 statistic, defined as the percentage of total variability across studies attributable to heterogeneity rather than chance, and used published guidelines for low (I^2 = 25%–49%), moderate (I^2 = 50%–74%) and high (I^2 > 75%) heterogeneity (Higgins et al., 2003). Individual study and pooled summary results are reported with 95% CIs ($CI_{95\%}$).

3. Results

3.1. Search results

One hundred nineteen unique articles were identified during the initial database search. Of these articles, 74 were excluded based on a screening of their title, leaving 45 abstracts to review. Sixteen of these articles were read in-full, of which, seven were deemed eligible for inclusion (Alnahdi et al., 2016; Bakirhan et al., 2012; Boonstra et al., 2008; Boonstra et al., 2010; Chu et al., 2013; Farquhar et al., 2008; van der Ven et al., 2017). Fig. 1 includes a flow diagram depicting the steps of the review process. Table 2 includes key details for the studies included in this review. Three studies (Alnahdi et al., 2016; Bakirhan et al., 2012; Farquhar et al., 2008) reported that subjects had received standard post-operative care and completed rehabilitation, with minimal detail regarding what this entailed; the remaining studies (Boonstra et al., 2008; Boonstra et al., 2010; Chu et al., 2013; van der Ven et al., 2017) did not provide details regarding post-operative care/rehabilitation.

Seven studies reported peak vGRF data (236 total subjects) (Alnahdi et al., 2016; Bakirhan et al., 2012; Boonstra et al., 2008; Boonstra et al., 2010; Chu et al., 2013; Farquhar et al., 2008; van der Ven et al., 2017). One of these studies (van der Ven et al., 2017) reported separate results for those who underwent conventional TKA and high-flexion TKA. In this case, data from both groups were included in the analysis. Only two studies (Alnahdi et al., 2016; Farquhar et al., 2008) reported peak knee extension moment data (89 total subjects).

3.2. Modified AXIS tool scores

Answers to the modified AXIS tool questions and total scores for each study included in this review are provided in Table 1. Scores ranged from 12 to 16 out of 17 (Table 1). All the studies met the proposed cutoff of 12 to be considered at least "good" quality.

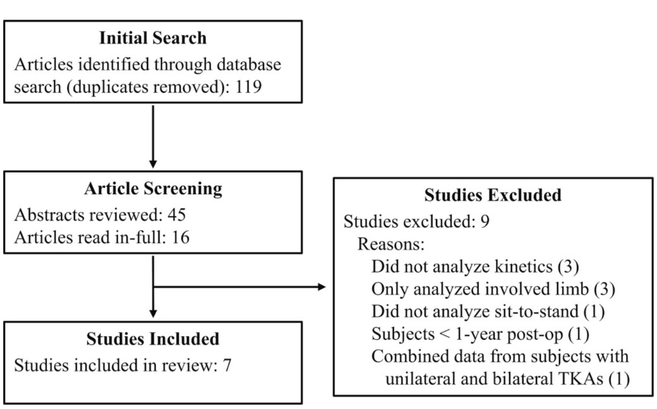

Fig. 1. Flow diagram depicting the article search and screening process.

3.3. Quantitative analysis

For the peak vGRF data, the pooled LSI was 0.96 ($CI_{95\%}$ = [0.93, 0.99], $p = 0.02$) with moderate heterogeneity (I^2 = 69%) (Fig. 2). For the peak knee extension moment data, the pooled LSI was 0.91 ($CI_{95\%}$ = [0.84, 0.98], $p = 0.01$) with no heterogeneity (I^2 = 0%) (Fig. 3). In both cases these findings reflect greater loading for the uninvolved limb/knee, relative to the involved limb/knee.

4. Discussion

The purpose of this systematic review and meta-analysis was to analyze the results of previous studies examining inter-limb kinetic symmetry during sit-to-stand performance among individuals who were at least one-year post-TKA. Based on the studies included in this review, limb/knee loading tended to be greater for the uninvolved limb vs. the involved limb during sit-to-stand performance, as the upper bounds of the 95% confidence intervals for the vGRF and knee extension moment LSIs were both <1.0, which reflects greater loading for the uninvolved limb relative to the involved limb. On average, the degree of inter-limb asymmetry was 4% (pooled LSI = 0.96) for the vGRFs and 9% (pooled LSI = 0.91) for the knee extension moments across the studies included in this review. In general, it appears that asymmetries in limb/knee loading tend to persist beyond the one-year post-operative period for individuals who have undergone TKA.

Previous studies have found that a relatively high proportion of patients who undergo TKA end up undergoing another joint replacement procedure in the future, often involving the contralateral knee or hip (Sayeed et al., 2011; Shakoor et al., 2002; Shao et al., 2013). For example, Sayeed et al. (2011) monitored subsequent orthopedic surgeries in 646 patients who had undergone unilateral TKA and found that almost 40% underwent a contralateral TKA within 10 years of their initial surgery. Another 2.4% underwent a contralateral total hip arthroplasty over the same period. While it is difficult to identify the primary cause of this observed trend, investigators have speculated that the tendency to shift load toward the uninvolved limb could help to explain, at least in part, why individuals who undergo TKA appear to be more susceptible to contralateral osteoarthritic changes over time (Alnahdi et al., 2016; Sayeed et al., 2011; Shakoor et al., 2002; Shao et al., 2013). It is possible that addressing the persistent asymmetry by training individuals to distribute load more evenly between the limbs following TKA could help to prevent some of these secondary musculoskeletal issues.

Deficits in quadriceps strength for the involved limb appears to be a primary contributor to kinetic asymmetry in the early post-operative period (Christiansen et al., 2011; Christiansen et al., 2013; Mizner and Snyder-Mackler, 2005; Pua et al., 2022) and two of the studies included in this review reported that subjects exhibited persistent deficits in quadriceps strength for their involved limb 1-year after undergoing TKA (Alnahdi et al., 2016; Farquhar et al., 2008). This suggests that unresolved deficits in quadriceps strength likely contribute to movement asymmetries after TKA. However, quadriceps strength asymmetry appears to be only weakly correlated with inter-limb kinetic asymmetry in the longer term. For instance, Alnahdi et al. (2016) found that quadriceps strength asymmetry only explained 4% of the variance in vGRF asymmetry ($r^2 = 0.04$) and 9% of the variance in knee extension moment asymmetry ($r^2 = 0.09$) in patients who were one-year post-TKA. Therefore, it appears that the persistent inter-limb kinetic asymmetries exhibited following TKA may be due, at least in part, to maladaptive motor control strategies that individuals adopt over time (perhaps even prior to surgery) to avoid knee loading (Alnahdi et al., 2016; Farquhar et al., 2008). This has important clinical implications, as it suggests that simply addressing peripheral impairments, such as quadriceps strength deficits, may not be sufficient for promoting inter-limb symmetry. Instead, there may also be a need to re-train an individual's underlying sensorimotor control systems.

Table 2
Key details for studies included in this review.

Article	Sample characteristics	Task details	Dependent variables
Alnahdi et al. (2016)	n = 77 (38 males, 39 females) Age: 65.6 ± 8.3 years Height: 1.7 ± 0.1 m Mass: 87.6 ± 15.3 kg BMI: 30.6 ± 4.7 kg/m^2 Time post-TKA: 1 year	5 sit-to-stand repetitions No use of arms for assistance during chair rising Chair height adjusted so knees flexed to 90° when seated	Peak vGRFs and peak knee extension moments Reported means for each limb and ratio of involved/uninvolved limb/ knee loading
Bakirhan et al. (2012)	n = 35 (all females) Age: 67.11 ± 3.97 Height: 156.34 ± 6.91 cm Mass: 75.71 ± 8.50 kg Time post-TKA: 1 year	3 sit-to-stand repetitions No use of arms for assistance during chair rising Sitting height adjusted so knees flexed to 90°	vGRFs Reported means for each limb
Boonstra et al. (2008)	n = 28 (11 males, 17 females) Age: 65.5 ± 8.9 years BMI: 29.7 ± 5.2 kg/m^2 Time post-TKA: 16.7 ± 5.7 months	10 sit-to-stand repetitions Chair did not have arm rests Chair height adjusted so knees flexed to 90° when seated	Peak vGRFs Reported ratio of involved/ uninvolved limb loading
Boonstra et al. (2010)	n = 16 (5 males, 11 females) Age: 65.4 ± 9.2 years BMI: 30.2 ± 4.9 kg/m^2 Time post-TKA: 13.2 ± 2.6 months	10 sit-to-stand repetitions No arm use for assistance during chair rising Chair height adjusted so knees flexed to 90° when seated	Peak vGRFs Reported ratio of involved/uninvolved limb loading (extracted from Boonstra et al., 2010 – fig. 2)
Chu et al. (2013)	n = 20 (7 males, 13 females) Age: 73 (38–89) years Time post-TKA: 1–2 years	3 sit-to-stand repetitions Subjects asked not to used their arms; however, some needed to 18-in. chair height	Peak vGRFs Reported ratio of involved/ (involved + uninvolved) limb loading
Farquhar et al. (2008)	n = 12 (6 males, 6 females) Age: 63 ± 6.9 (54–75) years Height: 1.70 ± 0.10 m Mass: 86.66 ± 10.18 kg BMI: 29.8 ± 4.1 kg/m^2 Time post-TKA: 1 year	No use of arms for assistance during chair rising Chair height adjusted to align with knee joint line height	Peak vGRFs Peak knee extension moments Reported ratio of involved/ uninvolved limb/knee loading
van der Ven et al. (2017)	*Conventional TKA group* n = 24 (13 males, 11 females) Age: 64 ± 7 years BMI: 31 ± 4 kg/m^2 Time post-TKA: 1 year *High-flexion TKA group* n = 24 (12 males, 12 females) Age: 66 ± 8 years BMI: 32 ± 5 kg/m^2 Time post-TKA: 1 year	Chair height adjusted so knees flexed to 90° when seated	Peak vGRFs Reported ratio of involved/ uninvolved limb loading

n = number of subjects; BMI = body mass index; TKA = total knee arthroplasty; vGRFs = vertical ground reaction forces
Mean ± standard deviation and/or (minimum-maximum)
Time post-TKA reflects the time from surgery to testing

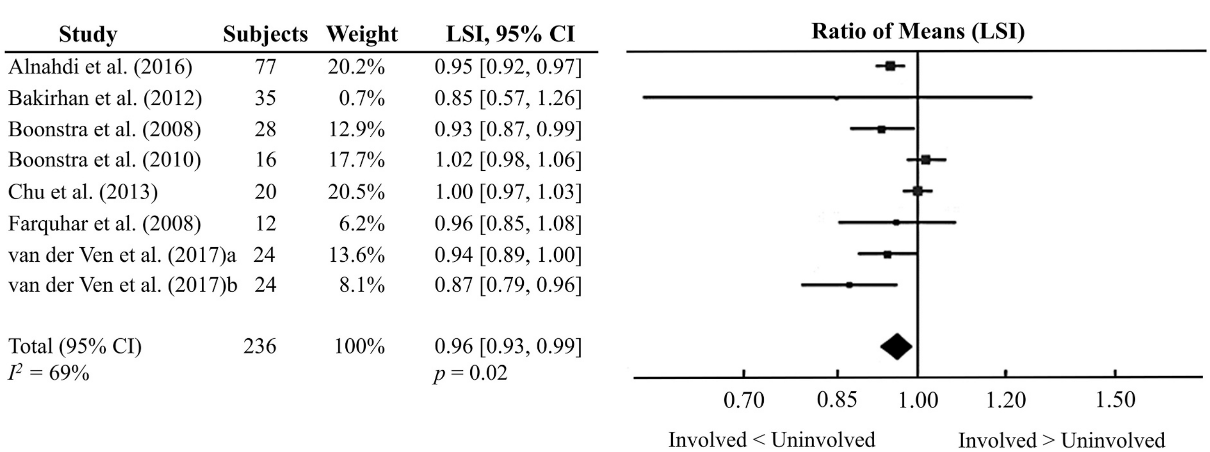

Fig. 2. Forest plot based on the peak vertical ground reaction force limb symmetry index (LSI) values for the studies included in this review. LSI values <1.0 reflect greater loading for the uninvolved limb vs. the involved limb. van der Ven et al. (2017)a relates to the conventional total knee arthroplasty group and van der Ven et al. (2017)b relates to the high-flexion total knee arthroplasty group.

Study	Subjects	Weight	LSI, 95% CI
Alnahdi et al. (2016)	77	94.4%	0.91 [0.84, 0.98]
Farquhar et al. (2008)	12	5.6%	0.82 [0.60, 1.12]
Total (95% CI)	89	100%	0.91 [0.84, 0.98]
$I^2 = 0\%$			$p = 0.01$

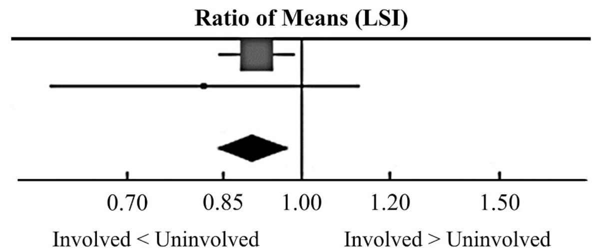

Fig. 3. Forest plot based on the peak knee extension moment limb symmetry index (LSI) values for the studies included in this review. LSI values <1.0 reflect greater loading for the uninvolved limb vs. the involved limb. Alnahdi et al. (2016) reported both the means for each limb and the mean of the limb loading ratios. The ratio of the means was used for analysis, in order to remain consistent in our approach. However, it is worth noting that the pooled results differ and are no longer statistically significant if the mean of the limb loading ratios is used instead of the ratio of the means (pooled LSI = 0.94; $CI_{95\%}$ = [0.88, 1.01]).

Conventional rehabilitation following TKA typically involves active/passive range of motion exercises, balance training, open and closed kinetic chain lower body strengthening, and transfer/gait re-training (Jette et al., 2020). However, these conventional rehabilitation approaches do not appear to be adequate for addressing inter-limb kinetic asymmetries. As a result, it may be important to explore novel approaches to more specifically address common movement asymmetries exhibited following TKA. For instance, real-time biofeedback regarding limb/knee loading symmetry has shown potential when used as an adjunct treatment during rehabilitation following TKA (Christensen et al., 2019; Christiansen et al., 2015; McClelland et al., 2012; Pfeufer et al., 2019; Zeni Jr et al., 2013). Zeni Jr et al. (2013) compared quadriceps strength symmetry, inter-limb kinetic symmetry, and functional mobility for patients with TKA who received real-time biofeedback training as part of their rehabilitation vs. those who received the standard-of-care which did not include real-time biofeedback training. The real-time biofeedback training involved providing patients with feedback related to their limb loading (e.g. visual display showing the load placed on each limb throughout a movement) during closed kinetic chain movements (e.g. leg press, double-leg squats, sit-to-stand) and asking them to try to maintain symmetrical limb loading. At the 6-month post-operative time point patients who received real-time biofeedback training exhibited more symmetrical quadriceps strength, greater movement symmetry, and improved functional mobility, suggesting that this type of movement pattern re-training may be an effective adjunct to conventional rehabilitation. There are also other approaches, aside from real-time biofeedback, that can provide additional sources of sensory information to the movement being trained (e.g. neuromuscular electrical stimulation), potentially impacting the complex sensorimotor processes in the central nervous system.

While the exact treatment parameters and mechanisms are not fully understood, there may also be benefits to incorporating stimulation to facilitate quadriceps activity/strength gains during the early post-operative rehabilitation period. Although quadriceps muscle function tends to improve throughout the course of rehabilitation, accelerating this process could help patients achieve the quadriceps muscle function needed for movement symmetry earlier, potentially helping them avoid additional iatrogenic movement compensations so they can begin reinforcing a symmetrical movement pattern more quickly after surgery. For example, application of neuromuscular electrical stimulation to the quadriceps shortly after TKA has been shown to accelerate quadriceps strength gains for the involved limb and promote improved functional performance over time (Klika et al., 2022; Stevens-Lapsley et al., 2012). Similar studies are being conducted to examine the effects of blood flow restriction therapy after TKA (e.g. Majors et al., 2022). While this modality is primarily considered for its impact on physiologic muscle adaptations, it also adds a profound augmented sensory stimulus to the movement being trained. This construct has only been scantly studied, but it is clear that blood flow restriction causes significant central nervous system activity (Hughes and Patterson, 2020). Again, these types of interventions to potentially impact central sensorimotor control processes and accelerate gains in quadriceps functioning after surgery could prove useful in helping patients develop the capacity to begin loading their involved limb/knee so they avoid the types of compensatory movement patterns that often persist following TKA.

There are also more subtle ways for rehabilitation professionals to promote involved limb/knee loading following TKA. For instance, shifting the foot position of the involved limb posteriorly could help to promote loading of the involved limb during sit-to-stand performance (Gillette and Stevermer, 2012; Jeon et al., 2019). This strategy could be beneficial for promoting involved limb loading if patients are performing sit-to-stands as a strengthening exercise. Elevating the foot position of the uninvolved limb could also be a useful strategy for encouraging loading of the involved limb during closed kinetic chain exercises such as squats (Brunt et al., 2002; Jean and Chiu, 2020). These types of subtle modifications to promote involved limb/knee loading are easy to implement with strengthening exercises commonly used after TKA. It may also be important for clinicians to assess whether patients have adequate strength for their involved limb before progressing from open kinetic chain exercises to double-leg closed kinetic chain exercises, as progressing before patients have adequate strength for their involved limb could result in overreliance on the uninvolved limb, potentially encouraging/reinforcing movement asymmetries. From a motor control perspective, it is important to remember that every repetition where load is shifted away from the involved limb reinforces this maladaptive motor pattern. Finally, progressing to more single-leg closed kinetic chain exercises could also help patients limit compensatory offloading of the involved limb.

In addition to advances in rehabilitation, future innovations in surgical techniques could also play a role in long-term recovery of movement symmetry after TKA. A preview of this may already be happening with anterior cruciate ligament (ACL) reconstructions. Similar persistent deficits in limb loading symmetry have been observed in individuals who have undergone ACL reconstruction (King et al., 2019), and interest has shifted to the proprioceptive role of the native ACL. Surgical techniques that spare ACL tissue are being developed, and initial outcomes are promising (Murray et al., 2020). For example, Goto et al. (2022) recently showed that individuals undergoing an ACL repair (which preserves the native ACL) had better limb loading symmetry 12 weeks post-operative, compared to a group undergoing standard ACL reconstruction. There has been similar interest in sparing cruciate ligaments during TKA (e.g. Parcells and Tria Jr., 2016) and it appears recent advances in next-generation bicruciate-retaining components has renewed interest in this approach (Sabatini et al., 2021). Future research is needed to determine what long-term impacts these techniques have on patient outcomes.

While the findings of this systematic review and meta-analysis are noteworthy and have important implications for rehabilitation professionals, the limitations of this review should be considered. First, it is important to acknowledge that while there appears to be a general pattern where patients tend to shift load toward the uninvolved limb, the extent to which this pattern of asymmetry contributes to subsequent musculoskeletal problems, functional limitations, etc. is unclear at this time. In some cases, the degree of asymmetry is probably too subtle to have a meaningful impact on long-term joint degeneration or function. Future studies should attempt to determine a threshold of asymmetry where outcomes after TKA start to become negatively impacted, so clinicians have a more objective cutoff for what should be deemed clinically relevant. Future studies may also incorporate other biomechanical variables, such as horizontal ground reaction forces, to develop a more complete understanding of movement adaptations following TKA. The relatively small number of studies eligible for inclusion in this review should also be noted. For the vGRF data, results were pooled from 236 subjects across seven studies, while for the knee extension moment data, results were pooled from 89 subjects across two studies. The findings of this analysis should continue to be re-evaluated as additional data becomes available. The lack of detail regarding the post-operative rehabilitation patients received for the studies included in this review also limits the inferences that can be made regarding the extent to which rehabilitation-related factors affect asymmetry. Finally, the sole focus on the sit-to-stand task could be viewed as a limitation. While sit-to-stand is a relatively demanding, highly functional, and well-studied task, there are other tasks that present unique challenges. For example, other tasks such as walking and stair ascent/descent should be examined to identify movement compensations that contribute to secondary musculoskeletal problems, functional limitations, etc. It may also be worth examining how symmetry during sit-to-stand correlates with movement adaptations during other functional tasks.

5. Conclusions

Based on the results of this systematic review and meta-analysis, it appears that inter-limb kinetic asymmetries during sit-to-stand persist beyond one year after TKA. In general, individuals who have undergone TKA tend to shift load toward their uninvolved limb/knee when transitioning from sitting to standing. This pattern of asymmetry could potentially contribute to degenerative changes for the uninvolved limb and negatively impact function. Rehabilitation professionals should consider ways to better address inter-limb asymmetries following TKA.

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Declaration of Competing Interest

None.

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