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## Kinematic and Kinetic Changes After Total Hip Arthroplasty During Sit-to-Stand Transfers: Systematic Review

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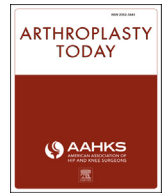
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## Systematic review

## Kinematic and Kinetic Changes after Total Hip Arthroplasty during Sit-To-Stand Transfers: Systematic Review

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## ABSTRACT

**Background:** Total hip arthroplasty (THA) is a common and effective surgical procedure that allows patients with hip osteoarthritis to restore functional ability and relieve pain. Sit-to-stand transfers are common demanding tasks during activities of daily living and are performed more than 50 times per day. The purpose of this systematic review is to obtain a comprehensive understanding of biomechanical changes during sit-to-stand transfers after THA.

**Methods:** Relevant articles were selected through MEDLINE, Scopus, Embase, and Web of Science. Articles were included if they met the following inclusion criteria: 1) participants underwent total hip arthroplasty without restriction on the arthroplasty design, 2) involved either kinematic or kinetic variables as the primary outcome measure, 3) evaluated sit-to-stand, and 4) were written in English.

**Results:** A total of 11 articles were included in the current systematic review. The THA group exhibited altered movement patterns as compared to healthy controls. Improvement in loading asymmetry was found up to 1 year after THA, but other kinetic changes indicate intensified contralateral limb loading. Limb differences were apparent, but whether these differences persist over 10 months after THA is still unknown.

**Conclusion:** Despite the inevitable changes in kinematics and kinetics in sit-to-stand transfers after THA, it appears to be important to resolve asymmetrical loading between the operative and nonoperative limbs to minimize risk for subsequent joint problems.

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## Introduction and background

Osteoarthritis (OA) is the most common degenerative joint disease in the elderly, affecting nearly 27 million Americans (12.1% of the adult population in the United States) [1,2]. In fact, hip OA could affect 19.6% of urban people older than 50 years in the United States [3]. Total hip arthroplasty (THA) is an effective operative procedure that allows patients with end-stage hip OA to improve function and relieve pain [4–6]. Although hip OA patients reported reduced pain level after THA, some patients reported decreased

quality of life because of limitations in activities of daily living even after THA [7,8]. These results suggest that improvement in pain does not necessarily result in restoration of functional ability of patients after THA. Therefore, assessing functional ability outcome is important to understand operative success after THA.

Sit-to-stand (STS) transfer is a common demanding task during activities of daily living and is performed more than 50 times per day [9,10]. STS transfers are related with quality of life or maintaining independent life [11]. STS strategies reflect important aspects for guiding clinical decision-making and evaluating hip function [12]. Accordingly, this movement has been commonly used to measure hip function of OA patients and identify poor operative outcomes in clinical settings. For example, STS is a common task involved in functional hip evaluations such as Western Ontario McMaster University Osteoarthritis Index, Hip

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disability and Osteoarthritis Outcome Score, and the Timed Up & Go test.

Previous biomechanical studies have investigated STS and reported that patients with THA exhibited decreased sagittal plane hip range of motion (ROM), frontal plane hip ROM, peak hip extension moment, hip power, vertical ground reaction force (VGRF), and VGRF symmetry for the operative limb as compared to controls [13–15]. When comparing pre-THA to post-THA, patients improved ipsilateral hip kinematics [16], loading (VGRF) asymmetry between limbs [14,17,18], and lateral trunk tilt [15]. In addition, significant differences between limbs (operative vs nonoperative limb) in kinetic variables were found at various time points dependent on time after THA [13,15,19]. These findings may support the idea that THA patients' nonoperative hip may subsequently develop OA and result in arthroplasty [20–22]. Although many studies have investigated STS in THA patients, there is no systematic review that summarizes the biomechanical abnormalities associated with the development of subsequent joint disease after THA.

The purpose of this review is to obtain a comprehensive understanding of biomechanical changes during STS transfers after THA. Specifically, the current review addresses the effect of time (between time points), the effect of groups (THA vs controls), and the effect of limbs (operative vs nonoperative limbs) on kinematics and kinetics. This review will provide a comprehensive summary of biomechanical changes after THA and thus may help design an effective rehabilitation program for THA patients.

**Material and methods**

*Search strategy*

This systematic review was performed according to the guidelines of the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) protocols [23]. The review search was conducted in March 2020 through MEDLINE (PubMed), Scopus (Elsevier), Embase (Elsevier), and Web of Science (Clarivate Analytics). To select articles, we used the search terms presented in Table 1. All articles were imported to Endnote X9 (Thomson Reuters, Carlsbad, CA), and duplicates were removed.

*Inclusion criteria*

Articles were included according to the following inclusion criteria:

1. Participants underwent THA, without restriction on the arthroplasty design.
2. Primary outcomes involved kinematic, kinetic, or muscle activity variables as measured by a 3D motion capture system, electrogoniometers, fluoroscopy, accelerometers, force plates, and/or electromyography (EMG).

**Table 1**  
Search keywords.

	Keywords
Activity	activities of daily living OR chair rise OR chair rising OR rising from a chair OR sit-to-stand
Measures	biomechanics OR kinetics OR kinematics OR Fluoroscopy OR motion analysis OR weight-bearing OR joint loading OR Electromyography OR EMG OR muscle strength
Population	hip arthroplasty OR hip prosthesis OR TKA OR total hip arthroplasty OR hip replacement OR total hip replacement OR THR OR prosthetic hip

**Table 2**  
Quality assessment scores.

Items	Reporting			External validity			Internal validity—bias					Internal validity—confounding			Total (%)	
	1	2	3	5	6	7	10	11	12	16	18	20	21	22		25
Study	1	1	0	0	1	1	1	0	0	1	0	1	0	0	1	8/16 (50)
Talis et al. (2007) [25]	1	1	1	1	1	1	1	0	0	1	1	1	1	0	1	12/16 (75)
Talis et al. (2008) [26]	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	14/16 (88)
Boonstra et al. (2011) [27]	1	1	1	2	1	1	1	0	0	1	1	1	0	0	1	12/16 (75)
Lamontagne et al. (2012) [13]	1	1	1	2	1	1	1	0	0	1	0	1	0	0	1	11/16 (69)
Caplan et al. (2014) [14]	1	1	1	1	1	1	1	0	0	1	1	1	0	1	1	12/16 (75)
Abujaber et al. (2015) [15]	1	1	1	1	1	1	1	0	0	1	1	1	0	1	1	12/16 (75)
Abujaber et al. (2017) [19]	1	1	1	1	1	1	1	0	0	1	1	1	0	1	1	12/16 (75)
Miura et al. (2018) [17]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15/16 (94)
Miura et al. (2018) [28]	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	13/16 (81)
Shiomoto et al. (2019) [16]	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	14/16 (88)
Temporiti et al. (2019) [18]	1	1	1	2	1	1	1	1	0	1	1	1	1	1	1	15/16 (94)
Mean																13/16 (78)

Items include the following questions: 1) Are the hypothesis/aims described clearly? 2) Are the main outcomes described clearly? 3) Are the characteristics of participants described clearly? 4) Are the characteristics of principal confounders described clearly? 5) Are estimates of the random variability provided? 6) Are the main findings described clearly? 7) Are estimates of the random variability provided? 8) Are actual probability values reported? 9) Were the participants asked to join the study representative of the entire population? 10) Were the participants asked to join the study representative of the entire population? 11) Were the participants asked to join the study representative of the entire population? 12) Were the participants preparing to participate representative of the entire population? 13) Was it clear if results were based on "data dredging"? 14) Were the measurements used for main outcomes accurate? 15) Were the study group and controls recruited from the same population? 16) Were the study group and controls recruited from the same population? 17) Were the study group and controls recruited from the same population? 18) Were the study group and controls recruited from the same population? 19) Were the study group and controls recruited from the same population? 20) Were the study group and controls recruited from the same population? 21) Were the study group and controls recruited from the same population? 22) Were the study group and controls recruited from the same population? 23) Were the study group and controls recruited from the same population? 24) Were the study group and controls recruited from the same population? 25) Was confounding adequately adjusted?

3. Experimental protocols included STS with a standard chair height condition.
4. Statistical analyses were performed.
5. The article was in English language and published in a peer-reviewed journal.

Only articles published to year 2020 were considered for further systematic review. There were no restrictions on age, gender, BMI, and hip arthroplasty design in the reviewed articles.

#### Methodological quality assessment

Two reviewers (J.W. and S.F.S.) independently assessed selected studies by using a modified version of Downs and Black quality checklist for health-care intervention studies [24]. Our modified version included 15 questions that were evaluated from the following subgroups: reporting (items 1, 2, 3, 5, 6, 7, and 10), external validity (items 11 and 12), internal validity (items 16, 18, and 21), and internal validity confounding (items 21, 22, and 25) (Table 2). These items were selected for their suitability for non-randomized and case control studies. A score of 1 or 0 was applied if the question answered “yes” or “no. For the item 5, a score of 2, 1, or 0 was placed if the question answered “yes”, “partially”, or “no”. The total score for the assessment was 16. Seventy-five percent or greater of the total score (12/16) was considered as the high quality, 60%–75% (10 or 11/16) was considered as the moderate quality, and 60% or less (0 to 9/16) was considered as low quality [29,30]. The Kappa coefficient was calculated to determine interrater reliability of the scores between the 2 reviewers. Thirteen relevant studies were finally selected for the quality assessment.

## Results

### Search results

The initial search identified 1192 articles through 4 electronic databases: MEDLINE (PubMed), Scopus (Elsevier), Embase (Elsevier), and Web of Science (Clarivate Analytics) (Fig. 1). After removing duplicates, 879 articles remained, and 2 reviewers (J.W. and S.F.S.) screened titles and abstracts. Seven more articles were discovered through citation analysis of relevant articles (as other resources in Fig. 1). A total of 836 articles were excluded because they did not meet our inclusion criteria (Fig. 1). We reviewed 43 articles in full text and then removed 32 articles because of reasons noted in Figure 1. Any discrepancies between reviewers were addressed and resolved by consensus. A total of 11 articles were included in this systematic review, but no data pooling or meta-analysis was performed because of a lack of homogeneity associated with the study outcomes, study design, and arthroplasty design across the included studies. Figure 1 displays our search and selection processes.

### Quality assessment

Eleven articles were evaluated with the 15-question modified Down and Black checklist. The results and summary from the quality assessment are represented in Table 2. Kappa's correlation was 0.84 for interrater agreement between the 2 reviewers. The mean quality score was 78% with a range from 50% to 94%. Most studies showed poor external validity scores (items 11 and 12). Three of the studies provided clarification about the source of population, and 4 studies indicated how the patients were selected. Also, most studies were poorly scored for internal validity confounding (items 21 and 22). Only 5 studies mentioned the patients were recruited from the same population. Ten studies were classified as high ( $\geq 75\%$ ) or moderate quality (60%–74%).

### Overview of studies

Details of the studies involved in this systematic review are presented in Tables 3 and 4. All studies examined STS movement after THA. The time since the hip surgery varied across the reviewed studies (3 days to 5 years). Five studies followed a cohort design [15–19], one of which included a healthy control group [15]. Six studies were case control studies [13,14,25–28] from which 4 focused on group differences between THA patients and healthy controls [13,25,26,28], one investigated differences between THA and revision THA [27], and one evaluated differences between THA and hip resurfacing arthroplasty [14]. Three studies also investigated limb differences between the operative and the nonoperative limbs [13,15,19]. Therefore, the main comparisons of interest in the reviewed studies were the effect of groups, effect of time, and effect of limbs. Sample size across the studies ranged from 7 to 158 for THA. All studies included THA, and only one study investigated the effect of bilateral THA vs unilateral THA [18].

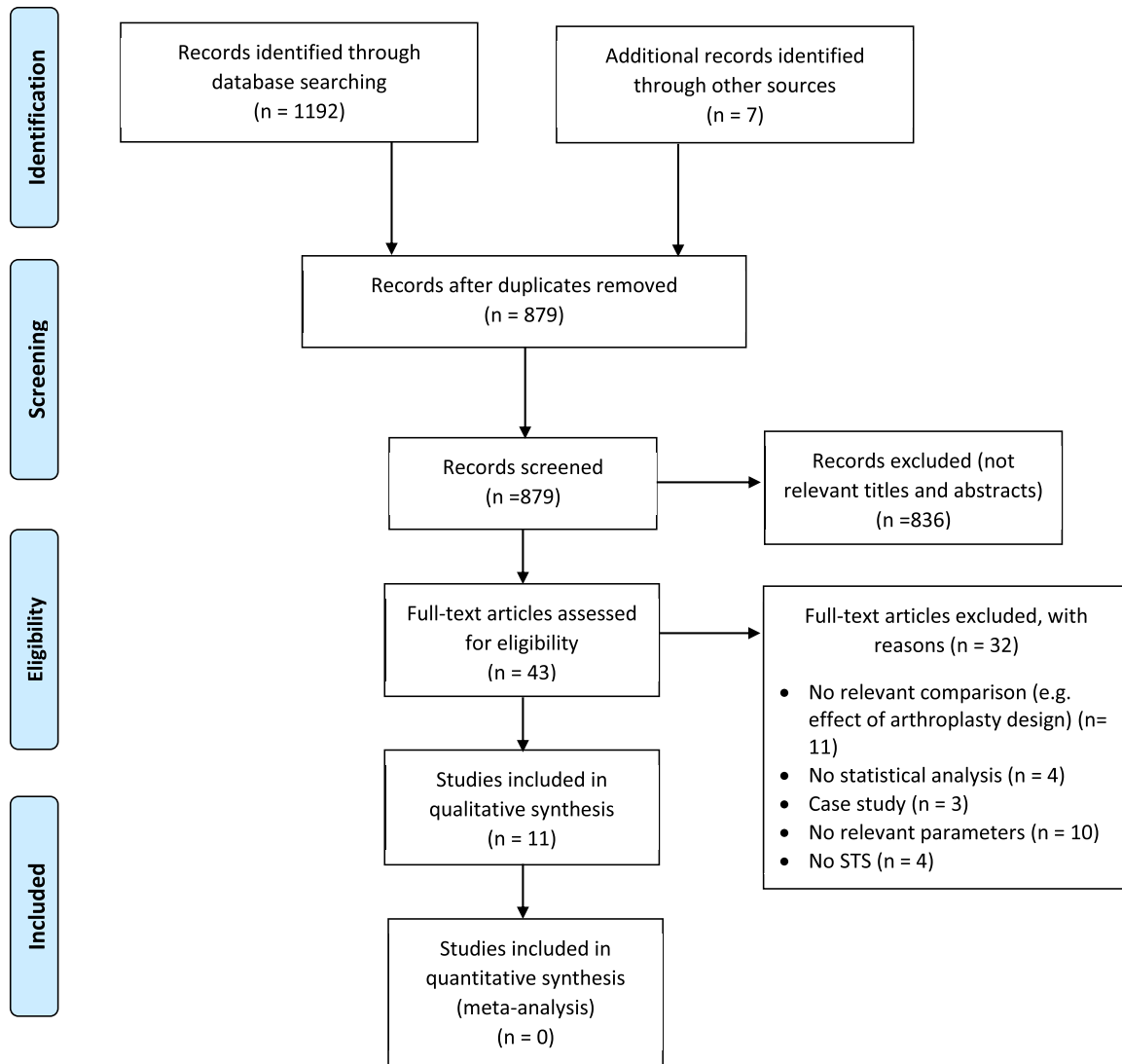
Kinematic and kinetic parameters were diversely examined in the reviewed studies (Table 3). Kinematic parameters included knee and hip kinematics: peak knee/hip flexion angles, average sagittal plane hip/knee angles, sagittal plane knee/hip ROM, peak knee/hip extension velocity, frontal plane hip ROM, and transverse plane hip ROM. Kinetic parameters involved peak knee extension moment, peak hip extension moment, peak knee adduction moment, peak VGRF, loading (VGRF) asymmetry/symmetry, and impulse symmetry. The most common parameter was the loading symmetry using VGRFs, and 7 studies assessed the loading symmetry between limbs using 3 parameters: symmetry ratio, asymmetry ratio, and loading distribution of the operative limb [14,17,18,25–28]. In addition, only one study examined hip kinematics in the frontal and transverse planes [13], and 2 studies reported hip kinetics in the frontal plane [13,19]. No studies evaluated muscle activity for THA during STS.

### Comparisons for THA vs controls

Out of the 11, a total of 6 studies reported differences between THA and healthy controls during STS transfers [13–15,25,26,28]. Lamontagne et al. reported changes in lower-limb kinematics and found decreased peak hip flexion (THA  $\approx 81.5^\circ$  vs control  $\approx 91.6^\circ$ ), decreased sagittal hip ROM ( $\approx 82.0^\circ$  vs  $90.9^\circ$ ), and increased frontal hip ROM ( $\approx 10.7^\circ$  vs  $8.5^\circ$ ) in the operative limb for 10 months after THA as compared to healthy controls [13]. For kinetic variables, this study also reported decreased peak hip extension moment ( $\approx 0.48$  Nm/kg vs  $0.67$  Nm/kg) and peak hip power ( $\approx 0.52$  W/kg vs  $0.93$  W/kg) in the operative limb for 10 months after THA as compared to controls [13]. Three studies reported decreased loading symmetry ( $\approx 0.77$  vs  $1.02$ ; complete symmetry = 1) when comparing 1–7 years after THA to controls [25,26,28], while one study found no differences in VGRF symmetry for 1 year after THA as compared to controls [14]. In addition, another study reported decreased peak VGRF ( $\approx 0.54$  N/kg vs  $0.61$  N/kg), peak hip flexion moment ( $\approx 0.39$  Nm/kg-m vs  $0.48$  Nm/kg-m), and peak knee extension moment ( $\approx 0.45$  Nm/kg-m vs  $0.54$  Nm/kg-m) in the operative limb for 3 months after THA as compared to controls [15]. Conversely, this study found increased peak VGRF ( $\approx 0.64$  N/kg vs  $0.60$  N/kg) and peak knee moment ( $\approx 0.58$  Nm/kg-m vs  $0.52$  Nm/kg-m) for the nonoperative limb for post-THA as compared to controls.

### Comparisons for multiple time points

Five studies examined the variables of interest at multiple time points [14–16,18,28]. Shiimoto et al. reported increased hip flexion ( $\approx 72.0^\circ$  vs  $62.8^\circ$ ) and decreased anterior-posterior pelvic tilt (anterior  $\approx 6.3^\circ$  vs  $11.7^\circ$ ; posterior  $\approx 14.5^\circ$  vs  $19.0^\circ$ ) for 62 months



**Figure 1.** Flow chart for search strategy results.

after THA as compared to pre-THA [16]. Abujaber et al. found decreased lateral trunk angle ( $\approx 3.95^\circ$  vs  $2.36^\circ$ ) from pre-THA to 3 months after THA [15]. This study also reported increased peak VGRFs ( $\approx 0.54$  N/kg vs  $0.51$  N/kg), peak hip flexion moment ( $\approx 0.39$  kg·m vs  $0.36$  kg·m), and peak knee flexion moment ( $\approx 0.45$  kg·m vs  $0.40$  kg·m) in the operative limb for 3 months after THA as compared to pre-THA [15]. Loading symmetry parameters (eg, VGRF symmetry/asymmetry/load distribution) were highlighted over various time points: pre THA, 3 days, 1 week, 1 month, 2 months, 3 months, 6 months, and 1 year after THA. The loading asymmetry increased from pre-THA to 1 week ( $\approx 0.14$  vs  $0.31$ ; complete symmetry = 0) [18]. Conversely, Caplan et al. reported increased loading symmetry when comparing 1 year to 3 months [14]. Similarly, Miura et al. found that load distribution of the operative limb (complete symmetry = 0.50) increased when comparing 6 months ( $\approx 0.45$ ) and 1 year ( $\approx 0.46$ ) to pre-THA ( $\approx 0.37$ ), 1 month ( $\approx 0.37$ ) after THA, and 2 months ( $\approx 0.42$ ) after THA [17].

#### Comparisons for operative vs nonoperative limbs

Differences between limbs (operative vs nonoperative) were one of the main comparisons in the studies [13,15,19]. The changes

between limbs were found in various kinematic and kinetic variables, but no EMG variables were reported. When comparing the operative to nonoperative limbs, frontal hip ROM increased at 10 months ( $\approx 10.7^\circ$  vs  $8.7^\circ$ ) but peak hip flexion angle decreased at 3 months ( $\approx 79.7^\circ$  vs  $82.4^\circ$ ) and 10 months ( $\approx 81.5^\circ$  vs  $83.4^\circ$ ) after THA [13,19]. Moreover, the included studies found decreased peak VGRF ( $\approx 0.52$  vs  $0.66$  N/kg), peak hip flexion moment ( $\approx 0.38$  vs  $0.46$  Nm/kg·m), peak hip extension moment ( $\approx 0.48$  vs  $0.66$  N/kg), and mean hip internal rotation moment ( $\approx 0.02$  vs  $0.05$  Nm/kg) at 3 months or 10 months after THA when comparing the operative limb to nonoperative limb [13,15,19]. For frontal plane hip kinetics, Lamontagne et al. found that peak hip adduction moment increased ( $\approx 0.16$  vs  $0.12$  Nm/kg) between the operative and nonoperative limbs at 10 months after THA while 2 other studies reported decreased hip adduction moment ( $\approx 0.09$  vs  $0.14$  Nm/kg·m) for the operative limb as compared to the nonoperative limb at 3 months after THA [13].

#### Discussion

The purpose of this study was to obtain a comprehensive understanding of biomechanical changes during STS movement after

**Table 3**  
Main instrumentation and variables.

	Instrumentation/surgical approach	Kinematic variable	Kinetic variable
Talis et al. (2007) [25]	Force platform NA	–	Loading asymmetry ratio
Talis et al. (2008) [26]	Force platform NA	–	Loading asymmetry ratio
Boonstra et al. (2011) [27]	Accelerometer/gyroscope Force platform NA	Peak knee extension velocity Peak hip extension velocity	Loading symmetry ratio
Lamontagne et al. (2012) [13]	Motion capture Force platform Lateral approach	Peak hip flexion angle Hip abduction angle at seat-on Peak knee flexion angle Sagittal plane hip ROM Frontal plane hip ROM Transverse plane hip ROM Sagittal plane knee ROM	Peak hip extension moment Peak hip adduction moment Mean hip internal rotation moment Peak knee extension moment Peak hip power Peak knee power
Caplan et al. (2014) [14]	Motion capture Force platform Lateral/anterolateral approach	–	Loading symmetry ratio Impulse symmetry ratio-
Abujaber et al. (2015) [15]	Motion capture Force platform Posterior/anterolateral/lateral approach	Lateral trunk angle	Peak vertical GRF Peak hip extension moment Peak hip flexion moment Peak knee flexion moment
Abujaber et al. (2017) [19]	Motion capture Force platform Posterior/anterolateral/lateral approach	Peak hip flexion angle Average sagittal hip angle Average sagittal knee angle Lateral trunk angle	Peak vertical GRF Peak hip flexion moment Peak hip adduction moment Peak knee flexion moment
Miura et al. (2018) [17]	Pressure platform Posterolateral approach	–	Load distribution of the involved limb
Miura et al. (2018) [28]	Pressure platform Posterolateral approach	–	Load distribution index
Shiomoto et al. (2019) [16]	Flat-panel Radiograph detector (image registration) Posterolateral approach	Peak AP pelvic tilt Peak hip flexion Pelvic tilt at peak hip flexion Hip abduction at peak hip flexion Hip external rotation at peak hip flexion	–
Temporiti et al. (2019) [18]	Motion capture Force platform Posterolateral approach	–	Load distribution index

NA, not available.

THA. The current review addressed changes in kinematic and kinetic changes when comparing multiple time points (before vs after THA), groups (THA vs controls), and limb (operative vs nonoperative limbs).

#### Comparisons for THA vs controls

Results from the current systematic review indicated significant differences in many kinematic and kinetic parameters between THA and controls. For kinematic variables, sagittal plane hip ROM and peak hip flexion were decreased, yet frontal plane hip ROM was increased for the operative limb for 10 months after THA as compared to controls [13]. However, as no other studies have investigated kinematic changes between THA and controls, there are still limited findings regarding lower limb kinematics after THA. Thus, further research with 3-dimensional kinematic analysis is needed to fully understand kinematic changes after THA.

Kinetic variables were popular in the included studies that found more adverse changes in various kinetic parameters such as peak VGRF, loading symmetry (VGRF symmetry), peak hip flexion/extension moment, peak hip power, and peak knee extension moment. Post-THA patients (1-7 years after surgery) showed decreased loading symmetry as compared to controls [25,26,28], although some patients did return to normal loading symmetry 1 year after the surgery [14]. However, the 2 studies [25,26] had a large variation in the time patients were recruited (0.1-7 years) since surgery. In addition, the discrepancy in results between previous studies exists and warrants further study to demonstrate

whether loading asymmetry is resolved at a specific time point after THA, with regard to healthy controls. THA patients also exhibited increased VGRF and peak knee flexion moment in the nonoperative limb [15] and decreased VGRF, hip flexion/extension moment, knee flexion moment, and hip power in the operative limb [13,15] when compared to controls. Along with results of the loading symmetry, these kinetic changes indicate that patients tend to avoid using their replaced hips while relying on the contralateral limb to minimize hip loading of the operative limb during STS.

There are no studies investigating muscle activity after THA as compared to healthy control during STS, suggesting further studies should include EMG analysis. When lifting the center of mass of the body against gravity, greater muscle strength and joint loading are required than for other daily activities [31]. Muscle weakness and abnormal muscle activity patterns after THA are related to limited functional ability [32-34]. Assessing muscle activation patterns while rising from a chair provide valuable insights into muscle deficit, coordination/coactivation, and compensatory strategies in patients after THA. A gait study found abnormal muscle activity of gluteus maximus, medius, and fascia lata in the operative limb (eg, greater activity and prolonged timing) as compared to the nonoperative limb after THA [34]. Another study also reported abnormal timing in the muscle activity of tibialis anterior, gastrocnemius lateralis, biceps femoris, and gluteus medius for THA as compared to controls during gait [32]. Furthermore, it is well known that hip muscle strength deficit (eg, hip extension, hip abductor) remains after full recovery [35,36], and thus it is critical to regain muscle strength and improve muscle control to maximize function after

**Table 4**  
Details about included studies.

Study	Sample				Comparison	Time points	Main study findings
	Size	Age (y)	Gender (M/F)	Height(kg) Weight(m) BMI			
Talis et al. (2006)	<ul style="list-style-type: none"> <li>• 17 THA (UNI)</li> <li>• 11 CON</li> </ul>	35-75 NA	NA NA	NA NA NA NA	• THA vs CON	• 1.5 mo-7 y	<ul style="list-style-type: none"> <li>• THA vs CON when comparing THA to CON</li> <li>• ↑ loading asymmetry</li> </ul>
Talis et al. (2008)	<ul style="list-style-type: none"> <li>• 27 THA (UNI)</li> <li>• 27 CON</li> </ul>	56 ± 10 55 ± 9	7/20 9/18	76.0 ± 10.0 1.65 ± 0.08 70.0 ± 12.0 1.68 ± 0.08 BMI	• THA vs CON	• 0.1-4 y (mean 19 mo)	<ul style="list-style-type: none"> <li>• THA vs CON when comparing THA to CON</li> <li>• ↑ loading asymmetry</li> </ul>
Boonstra et al. (2011) [27]	<ul style="list-style-type: none"> <li>• 10 THA (UNI)</li> <li>• 10 revision THA (UNI)</li> </ul>	57 ± 11 59 ± 12	8/2 7/3	25 ± 4 28 ± 4 BMI	• THA vs revision THA	<ul style="list-style-type: none"> <li>• mean 12.5 ± 1.2 mo</li> <li>• mean 18.8 ± 8.5 mo</li> </ul>	<ul style="list-style-type: none"> <li>• THA vs revision THA no changes in</li> <li>• peak knee extension velocity</li> <li>• peak hip extension velocity</li> <li>• loading symmetry ratio</li> </ul>
Lamontagne et al (2012) [13]	<ul style="list-style-type: none"> <li>• 20 THA (UNI)</li> <li>• 20 CON</li> </ul>	66 ± 7 64 ± 4	10/10 10/10	27.2 ± 5.0 24.5 ± 3.5 BMI	<ul style="list-style-type: none"> <li>• THA vs CON</li> <li>• OP vs non-OP limbs</li> <li>• males vs females</li> </ul>	• 6-15 mo (mean 10.4 ± 2.8 mo)	<ul style="list-style-type: none"> <li>• THA vs CON when comparing THA to CON</li> <li>• ↓ peak hip flexion angle on OP limb</li> <li>• ↓ sagittal plane hip ROM on OP limb</li> <li>• ↑ frontal plane hip ROM on OP limb</li> <li>• ↓ peak hip extension moment on OP limb</li> <li>• ↓ peak hip power on OP limb</li> <li>• ↓ peak hip flexion angle on non-OP limb</li> <li>• ↓ sagittal plane hip ROM on non-OP limb</li> <li>• ↓ peak hip power on non- OP limb</li> <li>• OP vs non-OP limbs when comparing OP to non-OP limbs</li> <li>• ↓ peak hip flexion angle</li> <li>• ↑ frontal plane hip ROM</li> <li>• ↓ peak hip extension moment</li> <li>• ↑ peak hip adduction moment</li> <li>• ↓ mean hip internal rotation moment</li> <li>• ↓ peak hip power</li> <li>• no change in peak knee extension moment</li> </ul>
Caplan et al. (2014) [14]	<ul style="list-style-type: none"> <li>• 7 THA (UNI)</li> <li>• 7 HRA (UNI)</li> <li>• 14 CON</li> </ul>	64 ± 8 55 ± 12 59 ± 10	7/0 5/2 12/2	89.3 ± 12.5 1.73 ± 0.09 84.7 ± 9.2 1.72 ± 0.08 77.1 ± 9.9 1.74 ± 0.07	<ul style="list-style-type: none"> <li>• THA/HRA vs CON</li> <li>• pre-THA/HRA vs 3 mo vs 1 y</li> </ul>	<ul style="list-style-type: none"> <li>• pre-THA/HRA</li> <li>• 3 mo</li> <li>• 1 y</li> </ul>	<ul style="list-style-type: none"> <li>• THA vs CON when comparing THA (3 mo) to CON</li> <li>• ↓ loading symmetry</li> <li>• ↓ impulse symmetry when comparing THA (1 y) to CON</li> <li>• no change in loading symmetry</li> <li>• no change in impulse symmetry</li> <li>• pre-THA vs 3 mo vs 1 y when comparing 1 y to 3 mo</li> <li>• ↑ loading symmetry</li> <li>• ↑ impulse symmetry when comparing 3 mo to pre-THA</li> <li>• ↑ impulse symmetry</li> </ul>
Abujaber et al. (2015) [15]	<ul style="list-style-type: none"> <li>• 44 THA (UNI)</li> <li>• 23 CON</li> </ul>	64 ± 8 68 ± 8	28/16 9/14	89.2 ± 22.1 1.74 ± 0.10 29.4 ± 5.6 71.4 ± 17.1 1.67 ± 0.09 25.3 ± 4.1	<ul style="list-style-type: none"> <li>• pre-THA vs 3mos</li> <li>• OP vs non-OP limbs</li> <li>• THA vs CON</li> </ul>	<ul style="list-style-type: none"> <li>• pre-THA</li> <li>• 3 mo</li> </ul>	<ul style="list-style-type: none"> <li>• THA vs CON when comparing THA to CON</li> <li>• ↓ peak VGRF for OP limb</li> <li>• ↓ peak hip flexion moment for OP limb</li> <li>• ↓ peak knee flexion moment for OP limb</li> <li>• ↑ peak VGRF for non-OP limb</li> <li>• ↑ peak knee flexion moment for non-OP limb</li> <li>• pre-THA vs 3 mo when comparing 3 mo to pre-THA</li> <li>• ↑ peak VGRF for OP limb</li> <li>• ↑ peak hip flexion moment for OP limb</li> <li>• ↑ peak knee flexion moment for OP limb</li> <li>• ↓ peak VGRF for non-OP limb</li> <li>• ↓ peak hip flexion moment for non-OP limb</li> <li>• ↓ later trunk angle</li> <li>• OP vs non-OP limbs when comparing the OP limb to the non-OP limb</li> </ul>

(continued on next page)

Table 4 (continued)

Study	Sample				Comparison	Time points	Main study findings
	Size	Age (y)	Gender (M/F)	Height(kg) Weight(m) BMI			
Abujaber et al. (2017) [19]	• 27 THA (UNI)	62 ± 8	15/12	90.7 ± 22.2 1.74 ± 0.10 29.9 ± 5.8	• OP vs non-OP limbs	• 3 mo	<ul style="list-style-type: none"> <li>• ↓ peak VGRF</li> <li>• ↓ peak hip flexion moment</li> <li>• ↓ peak hip adduction moment</li> <li>• ↓ peak knee flexion moment</li> <li>• ↓ peak knee flexion moment</li> <li>• OP vs non-OP limbs when comparing the OP limb to non-OP limb</li> <li>• ↓ peak hip flexion angle</li> <li>• ↓ peak VGRF</li> <li>• ↓ peak hip flexion moment</li> <li>• ↓ peak hip adduction moment</li> <li>• ↓ peak knee flexion moment</li> </ul>
Miura et al. (2018) [17]	• 158 THA (UNI)	62 ± 10	15/143	55.6 ± 8.0 1.55 ± 0.10 23.0 ± 2.7	• pre-TKA vs 1 mo vs 2 mo vs 3 mo vs 6 mo vs 1 y	• pre-THA • 1 mo • 2 mo • 3 mo • 6 mo • 1 y • 1 y	<ul style="list-style-type: none"> <li>• pre-TKA vs 1 mo vs 2 mo vs 3 mo vs 6 mo vs 1 y when comparing 6mos and 1 y to pre-THA, 1 mo, 2 mo</li> <li>• ↑ load distribution of the OP limb when comparing 1 y to 3 mo, when comparing 2 mo &amp; 3 mo to 1 mo &amp; 2 mo</li> <li>• ↑ load distribution of the OP limb</li> </ul>
Miura et al. (2018) [28]	• 28 THA (UNI) • 16 CON	62 ± 10 67 ± 7	0/28 0/16	53.6 ± 6.8 1.53 ± 0.06 22.7 ± 2.6 51.7 ± 4.6 1.55 ± 0.05 21.5 ± 1.9	• THA vs CON	• 1 y • 1 y	<ul style="list-style-type: none"> <li>• THA (1 y) vs CON when comparing THA to CON</li> <li>• ↓ loading symmetry</li> </ul>
Shiomoto et al. (2019) [16]	• 21 THA (UNI)	67 ± 8	5/16	57.0 ± 12.0 1.56 ± 0.09 24.0 ± 4.0	• pre-THA vs 62 mo	• pre-THA • 47–76 mo (mean 62 ± 11 mo)	<ul style="list-style-type: none"> <li>• pre vs 62 mo when comparing 62 mo to pre-THA</li> <li>• ↑ peak hip flexion</li> <li>• ↑ peak anterior pelvic tilt</li> <li>• ↓ peak posterior pelvic tilt</li> <li>• ↑ anterior pelvic tilt at peak hip flexion</li> </ul>
Temporiti et al. (2019) [18]	• 20 UNI THA • 20 BI THA	53 ± 6 52 ± 6	14/6 18/2	78.3 ± 12.7 1.71 ± 0.09 81.7 ± 14.8 1.76 ± 0.08	• pre-THA vs 3 d vs 7 d • UNI vs BI THA	• pre-THA • 3 d • 7 d	<ul style="list-style-type: none"> <li>• pre-THA vs 3 d vs 1 wk when comparing 3 d &amp; 1 wk to pre-THA</li> <li>• ↓ loading symmetry</li> <li>• UNI THA vs BI THA when comparing UNI to BI THA</li> <li>• ↓ loading symmetry</li> </ul>

BI, bilateral; CON, control group; HRA, hip resurfacing arthroplasty; NA, not available; OP, operative; non-OP, nonoperative; UNI, unilateral.



surgery. In this regard, a more comprehensive analysis including EMG data is needed to obtain a comprehensive understanding of biomechanical changes after THA during STS. Overall, considering all changes in kinematics and kinetics, functional ability of the hip after THA is still limited during STS transfers.

#### *Comparisons for time points*

Despite kinematic and kinetic differences between THA and controls, significant improvement was found over time (as compared to pre-THA) evidenced by increased hip flexion, decreased pelvic tilt, and decreased lateral trunk flexion after THA as compared to those before THA [15,16]. The improvement in kinetic variables was also found over multiple time points of recovery (2 months–1 year) in literature. For example, better VGRF symmetry (between limbs) was found at 2 months after THA as compared to before THA, and the improvement in the loading symmetry was continued up to 1 year after THA evidenced by increased VGRF symmetry ratio for 1 year as compared to 1, 2, and 3 months after THA [17]. However, the loading symmetry was decreased for 3 months after THA as compared to healthy controls [14], which indicates that loading asymmetry still exists at 3 months after THA. The asymmetry in VGRFs is due to an offloading strategy for the operative limb while there is increased load on the operative limb after THA. In addition, it is unclear if the loading asymmetry is resolved by 1 year of recovery when analyzed in conjunction with the comparison between 1-year post-THA data and controls because of inconsistent results between previous studies [14,25,26,28], so it remains to be seen whether the patients resolve the loading asymmetry beyond 1 year of recovery. Furthermore, findings in lower limb joint moments over time were limited as only one study investigated lower limb kinetics in the sagittal and frontal planes [15]. Thus, future investigation should include 3-dimensional kinetic analyses with long-term follow-up to provide a complete picture of the time course of functional recovery.

#### *Comparisons for operative vs nonoperative limbs*

The current review also highlighted apparent differences between the operative and the nonoperative limbs during STS. By 3 months of recovery, 2 studies found decreased VGRF, hip flexion moment, hip adduction moment, and knee flexion moment for the operative limb as compared to the nonoperative limb [15,19]. In 6–15 months of recovery, the THA group showed increased frontal plane hip ROM with decreased hip flexion angle for the operative limb as compared to nonoperative limb [13]. Also, decreased hip extension moment, hip internal rotation moment, and hip extension power were found for the operative limb in 6–15 months after THA [13]. For frontal plane hip kinetics, 2 studies found decreased hip adduction moment for the operative limb at 3 months after THA [15,19], but another study reported increased hip adduction moment for the operative limb compared with the nonoperative limb 10 months after THA [13]. The discrepancy in the results between the studies may be due to different time points (3 months vs 10 months after THA), which may be associated with decreased hip abductor muscle strength for the operative limb over time [37].

Asymmetries in the kinematic and kinetic parameters between limbs were found in early recovery (3 months after the surgery) and appeared to remain 10 months after THA. These results may be associated with potential risk for development of subsequent joint problems, particularly in the contralateral limb. In fact, a recent epidemiological study indicated that almost 20% of patients underwent THA for the other hip within 5 years of initial THA. Thus, it appears to be important to improve asymmetric loading mechanisms between limbs to minimize the risk for subsequent joint

problems and need for arthroplasty. Adverse changes in kinematic and kinetic variables were reported up to 10 months after THA and whether these changes persist after 10 months after THA is unknown. Thus, further investigation is required to examine asymmetrical loading mechanisms between limbs with long-term follow-up. As with other comparisons for THA vs control and for time points, there is a great need to assess muscle activity to help develop effective rehabilitation programs aimed at resolving the asymmetry in joint loading between limbs.

#### **Conclusions and future directions**

To the best of our knowledge, this study is the first to summarize previous findings in kinematics and kinetics during STS transfers after THA. The current review found a variety of changes in comparisons between THA vs controls, time points since THA (eg, preoperative, postoperative), and operative vs nonoperative limbs. The THA group exhibited altered movement patterns compared with controls, which indicates that the functional ability of the hip after THA may not return to normal. Considering the time course of recovery, improvement in VGRF asymmetry was found 2 months–1 year after the surgery, but it is not clear if the loading asymmetry is resolved when compared to healthy controls. Limb differences were apparent and still remain at 10 months, indicating intensified contralateral limb loading.

There are limitations of the current review. Owing to a lack of homogeneity associated with the study outcomes, study design, and time points of follow-up across the studies, we were not able to perform a meta-analysis. Thus, this review still has limits to its generalizability. Another limitation is that the selected variables in this review may be biased, but the kinematic and kinetic variables may provide comprehensive lower extremity mechanics after THA. Also, we did not consider different surgical approaches (anterior vs posterior vs lateral approach), which is another important compounding factor and could result in different surgical outcomes and muscle deficit [38–40]. Finally, we did not consider different arthroplasty designs, rehabilitation programs, and populations (eg, normal weight vs obese patients) that could affect the study outcomes.

Based on our systematic findings of this review, several directions for future research are suggested. First, findings of this review are limited to kinematics and kinetics, and thus, future studies should assess lower extremity muscle activity with comparisons between THA vs controls, between time points, and between the operative limb vs nonoperative limb to understand abnormal lower limb mechanics associated with subsequent joint disease. Second, there is a need for a longitudinal study investigating kinematic, kinetic, and muscle activity variables at different time points. Although one study followed up THA patients at 6 different time points (pre-THA, 1, 2, 3, 6, and 12 months), most studies were limited to 2 time points (preoperative vs postoperative) in the previous longitudinal studies. Third, most studies (7 out of 11 studies) reported only one kinetic parameter: VGRF symmetry. However, the VGRF is a whole-body parameter, so without an additional video analysis, we are unable to identify where abnormal loading mechanisms in the body are intensified. Finally, 2 studies reported changes in VGRF symmetry between THA vs revision THA and between THA vs resurfacing hip arthroplasty groups. Therefore, it is of interest to investigate biomechanical differences between these groups to assess differences in functional ability and determine optimal functional outcome. The results of this review will hopefully improve understanding of alterations in kinematics and kinetics after THA during STS and thus may serve as the basis for future investigation aimed at understanding functional recovery of lower extremities after THA and optimization of hip joint replacement.

## Conflict of interests

E. Mannen received research support from Medtronic. C. L. Barnes received royalties from DJO, Medtronic, and Zimmer; is a paid consultant for Health Trust, Medtronic, and Responsive Risk Solutions; has stock or stock options in Responsive Risk Solutions; received research support from ConforMIS; received financial or material support from Corin-Non-PI; is in the Medical/Orthopedic publications editorial board of JOA and JSOA; and is a board or committee member of AAHKS, HKA Foundation, MAOA, and SOA.

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