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Review

Gait analysis of patients following total knee replacement: A systematic review

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Abstract

Gait analysis has been used to objectively measure patients' function following total knee replacement (TKR). Whilst the findings of this research may have important implications for the understanding of the outcomes of TKR, the methodology of existing research appears to be diverse and many of the results inconsistent. The objective of this systematic review was to synthesise reported findings and to summarise the methods used by researchers in this field. Eleven articles published in the medical literature that used gait analysis to compare patients following TKR with controls were identified for inclusion in this review. Each article was assessed for methodologic quality and data was compared across studies through the calculation of effect sizes. Consistently large effect sizes showed that patients following TKR walk with less total knee motion during gait and with less knee flexion during swing than controls. Kinetic discrepancies between patients and controls were also identified. The substantial methodologic differences between studies may contribute to the inconsistencies in reported findings for many gait outcomes. Future research is needed to determine the clinical relevance of these findings.

Keywords: Total knee replacement; Gait analysis; Gait; Systematic review; Biomechanics

Contents

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1. Introduction

Total knee replacement (TKR) is a widely used intervention in the management of knee osteoarthritis. The increasing prevalence of TKR highlights the need to appropriately assess post-operative outcome of this procedure [1]. Gait analysis is a tool that has been used by researchers to measure functional outcome following TKR. It has been proposed that gait analysis is valuable in the clinical management of patients undergoing TKR through its ability to monitor forces through the knee [2]. In particular, the adduction moment across the knee has received attention due to its association with TKR component loosening [3].

Despite the potential usefulness of gait analysis, there are marked discrepancies in the research methods that have been reported. Variations in subject characteristics, prosthetic designs and methodology of gait analysis make comparison of findings between studies difficult. Nonetheless, assessment of TKR patients using gait analysis continues to be reported. It is therefore important to identify discrepancies between studies to allow for more appropriate comparison of findings and potentially to assist in directing future research. To date there has been no attempt to systematically review the findings of gait analysis in patients following TKR. The aim of this systematic review was therefore to identify common themes in the methods of research in the gait analysis of TKR patients and to summarise the findings reported in this literature.

2. Materials and methods

2.1. Literature search strategy

A search for articles on gait analysis in patients following TKR was completed in September 2006. The databases of Medline, Cinahl, Embase, Current Contents, Pedro, and The Cochrane Library were searched for full text articles published in English using combinations and variations of the following terms: knee arthroplasty, knee replacement, knee prosthesis, knee implant, gait, locomotion, walking, biomechanics, kinetics, kinematics, angle, moment and torque. These electronic searches were supplemented by cross-checking citations and reference lists of the relevant published studies. Details of all articles returned from the searches were saved for application of the following selection criteria.

2.2. Selection criteria

To be included in the final review, studies had to present original raw data, investigate patients who were at least 6 months following TKR predominantly for osteoarthritis, compare TKR patient data to an unimpaired control population, and describe the kinematic or kinetic characteristics of the knee during level gait with simultaneously collected spatiotemporal data.

These selection criteria were chosen to allow comparison of findings between studies with minimal influence of confounding factors. Studies that did not present original data were excluded to minimise the potential bias of their data in cross-study comparisons. The most common indication for TKR is a diagnosis of knee osteoarthritis (OA) [1]. Since the effect on gait of other indications for TKR remains unclear, only studies where greater than 75% of the sample received a TKR for OA were included. Studies in which patients were assessed less than 6 months following knee arthroplasty were excluded because the patients could not be considered adequately rehabilitated. Only studies that compared the biomechanics of patients to that of a healthy control population were included in this review to allow calculation of effect sizes. As the velocity of a person's walking speed can alter the biomechanics of lower limb joints [4], only studies that reported knee biomechanics with reference to spatiotemporal parameters (speed, stride length or cadence) were included.

These selection criteria were applied to the title and abstract of all articles retrieved in the search of the literature. The full text articles not excluded in this initial selection process were then evaluated for inclusion using the same selection criteria.

2.3. Assessment of methodological quality

The methodological quality of each study was assessed using a validated assessment tool. In a comprehensive search of the literature four possible tools that could assess the methodological quality of non-randomised trials were identified [5–8]. The checklist by Downs and Black was selected for its reported inter-rater and intra-rater reliability [5]. Only the criteria relevant to assessing potential sources of bias in non-randomised studies were applied. In this review, the assessment of methodological quality was principally to identify common themes in the methods used in this field of research.

2.4. Data extraction and analysis

A form was developed to standardise the amount and type of data extracted. A meta-analysis of reported findings was not performed due to the heterogeneity of studies' designs and methods. The effect sizes of patient group mean scores compared to control group mean scores were calculated where sufficient data was reported. The effect size calculator developed by The Curriculum, Evaluation and Management Centre [9] was used for this purpose.

Two reviewers (JAM and an independent non-author reviewer) performed the selection process, assessment of methodologic quality and data extraction to minimise the potential for bias. Disagreements between reviewers were resolved by discussion with a third reviewer (KEW).

3. Results

Eleven studies were accepted for inclusion in this systematic review. Table 1 summarises results from the assessment of methodologic quality for each of these studies. All studies satisfied a similar number of criteria, yet the methodology varied substantially across studies.

Although all studies stated the aim of the research, there were marked differences in the research objectives – four aimed to describe the gait of patients with total knee arthroplasty [10–13] and six aimed to compare different aspects of prosthetic design, pre-operative diagnosis or timing of surgical intervention [14–19]. All but one [17] of the studies described subjects adequately in terms of

Table 1
Assessment of methodologic quality

Downs and Black [5] criteria	Item no. 1	Item no. 2	Item no. 3	Item no. 5	Item no. 6	Item no. 7	Item no. 12	Item no. 16	Item no. 18	Item no. 25	Item no. 27
First author (year)	Clear aim	Outcomes described	Patients described	Confounders described	Main findings clearly described	Measures of random variability	Subjects represent population	Planned analysis	Appropriate statistics	Adjustment for confounders	Power calculation
Bolanos et al. [15]	✓	×	✓	×	✓	×	×	✓	✓	✓	×
Borden et al. [16]	✓	✓	✓	✓	✓	✓	×	✓	✓	×	×
Brugioni et al. [24]	✓	✓	✓	×	×	×	×	✓	✓	✓	×
Chassin et al. [17]	✓	✓	×	×	✓	×	×	✓	✓	✓	×
Chen et al. [18]	✓	×	✓	✓	✓	×	×	✓	✓	×	×
Fuchs et al. [10]	✓	✓	✓	×	✓	✓	×	✓	✓	×	×
Fuchs et al. [19]	✓	×	✓	✓	×	✓	×	✓	✓	×	×
Saari et al. [14]	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	×
Simon et al. [11]	✓	✓	✓	✓	✓	×	×	×	✓	×	×
Smith et al. [12]	✓	✓	✓	✓	✓	✓	×	✓	✓	×	×
Wilson et al. [13]	✓	✓	✓	✓	✓	×	×	✓	✓	✓	×

diagnosis, time at follow-up, prosthetic design, and contralateral knee involvement. Despite this, no study reported evidence that the subjects were representative of the target population.

An important aspect of research is identifying and minimising factors that may confound results. The effects of subjects' age, gender, height and weight on gait and the need to adequately control for these factors are well documented in the broader gait literature [20–23]. Although eight of the ten studies reported the age and gender of subjects, six did not report subject height [10,13–15,17,24], and four of these did not report subject weight [10,15,17,24]. Additionally, only one study [12] reported that patients and controls were comparable for these factors at baseline. Controlling for these differences between groups was also inconsistently reported. Five studies adjusted for subjects' bodyweight only [12,14,16,18,19], two studies adjusted for subjects bodyweight and height [17,24], two studies adjusted for subjects bodyweight and leg length [12,15] and the three remaining studies did not report on adjustment for body weight or height [10,11,25].

There were also discrepancies in the way authors described relevant outcome measures and reported findings. This was particularly evident in the selection of the number of walking trials used for analysis. Five studies analysed a single trial – three reported that selection was determined by speed [14,17,24], one reported that the best trial was chosen [11] and one analysed the only trial captured [10]. In contrast, three studies analysed an average of multiple trials – one analysed the average of three trials [16], one analysed the average of between five and eight trials [12] and the remaining study did not specify the number of trials averaged [15]. The effect of this discrepancy on results has not been determined.

3.1. Study design

Table 2 summarises the design features of each study included in this review. This table demonstrates the diversity within the literature, particularly with regard to the differences in prosthetic design. Also of interest is the lack of consistency with regard to inclusion of patients with bilateral TKR. Three studies assessed only bilateral TKR patients [15,16,18], three studies excluded patients with bilateral TKR [10,11,19] and the remaining 5 studies included varying proportions of bilateral TKR patients.

3.2. Outcome measures

In addition to the variations in research methods and study design, there was a wide range of gait outcomes reported. Table 3 lists the twenty-nine biomechanical outcome measures that were reported across the eleven studies. Results of comparisons between patient and control groups are shown in Table 4. To identify the consistency of these findings, only outcome measures that were reported in three or more studies are presented. Given the ongoing debate about the effect of retaining or resecting the posterior cruciate ligament (PCL) in TKR the findings of this review are presented to reflect these patient groups.

3.3. Walking speed

The effect of walking speed on biomechanics during gait is well documented and is therefore an important consideration when comparing subject groups. This review identified a lack of consistency in the determination of walking speed during data collection. Two studies reported that subjects were instructed to walk at a constant speed [10,16]. Two studies selected patient walking trials that were of similar speed to controls [17,24]. One study reported that the control group subjects were instructed to walk at a pace similar to the pre-recorded patient group subjects [12]. One study did not specify how walking speed was determined [11] and the remaining studies reported analysis of results from subjects and controls walking at a self-selected comfortable speed. It is, however, interesting to note that all patients groups across these five studies that reported results at patients' self-selected speed walked at a similar pace to each other (0.8–1.1 m/s). Furthermore, when compared to their respective control groups, eight of the eleven patient groups walked at a significantly slower speed [14,15,18,19].

3.4. Gait analysis protocols

Table 5 summarises the protocol of gait analysis reported by authors. There was an obvious lack of sufficient reporting protocol details. Despite this, large variations were seen in the frequency of kinematic data collection (50 to 240 Hz), kinetic data collection frequency (50 to 2000 Hz), and the number of trials included in

Table 2
Study design and patient characteristics

Author (year)	Nation	Prosthetic make	Design	No. surgeons	Sample size	No. controls	Subject characteristics: Bilateral TKR inclusion	No. OA/RA	Clinical rating	Time of gait analysis from surgery
Bolanos et al. [15]	USA	Insall-Burstein II	PCL-resected (posterior stabilised)	1	14 knees	16	All bilateral	10OA/4RA	HSS ≈ 93	98 months (72–134 months)
		Anatomic Graduated, Cruciate Condylar, Kinematic Condylar	PCL-retained		14 knees					
Borden et al. [16]	USA	PCA Modular, Kinematic, Duracon	PCL-retained	1	13 patients	9	All bilateral	12OA/ 1RA	Not reported	46 months [a] (30–72 months), 64 months [b] (19–168 months), 86 months [c] (24–153 months)
Brugioni et al. [24]	USA	Total condylar	PCL status unknown	1	21 knees	15	7 bilateral	OA only	not reported	18 months (12–22 months)
Chassin et al. [17]	USA	Not stated	Not stated	Not stated	29 patients	35	Not stated	OA only	HSS ≥ 90	19 months (7–47 months)
Chen et al. [18]	Taiwan	Insall-Burstein	PCL resected (Posterior stabilised)	1	9 knees	40	All bilateral	OA only	Not reported	40.4 months
		Miller-Galante	PCL-retained		9 knees					
Fuchs et al. [10]	Germany	Genesis-I	PCL-retained	Not stated	19 patients	22	Bilateral excluded	OA only	Not reported	24.6 ± 16.7 months
Fuchs et al. [19]	Germany	GSB	PCL-resected (posterior stabilised)	1	15 patients	11	Bilateral excluded	OA only	Not reported	31.9 months (Sledge), 26.7 months (GSB)
		Sledge	PCL-retained		15 patients					
Saari et al. [14]	Sweden	AMK	PCL-resected	Not stated	12 knees	18	3 bilateral	OA only	HSS not different between groups	1–2 years
			PCL resected (posterior stabilised)		9 knees					
			PCL-retained		11 + 9 knees					
Simon et al. [11]	USA	Duopatellar, Duocondylar	PCL-retained	Not stated	12 patients	15	Bilateral excluded	OA only	not reported	39 months (26–77 months)
Smith et al. [12]	Australia	Profix	PCL status unknown	2	41 knees	20	7 bilateral	OA only	not reported	12–18 months
Wilson et al. [13]	USA	Insall-Burstein II	PCL-resected (posterior stabilised)	1	16 patients	16	3 bilateral	OA only	HSS ≈ 93	46 months (range 22–98 months)

TKR, total knee replacement; PCL, posterior cruciate ligament; OA, osteoarthritis; RA, rheumatoid arthritis; HSS, Hospital for Special Surgery Score; KSS, Knee Society Score.
[a] Simultaneous bilateral TKR.
[b] Right limb staged bilateral TKR.
[c] Left limb staged bilateral TKR.

analysis (1–5). One study collected data from subjects walking on a treadmill [10].

3.5. Knee biomechanics

Table 4 summarises the biomechanical findings reported by authors when comparing TKR patient groups to controls. Common trends that were evident in this table were investigated further as described below.

3.5.1. Kinematic data

Comparison of kinematic findings across studies was possible through the calculation of effect sizes using the patient group and the control group means. Effect sizes were calculated for all measures where sufficient data were reported for more than two patient groups of each prosthetic design type. These were the total range of knee motion during gait; the maximum knee flexion during the swing phase; the maximum knee flexion during the stance phase; and the range of flexion during the loading phase. Forest plots for these measures are shown in Figs. 1–4. Fig. 1 clearly shows that all studies reported that the patient groups walked with less total range of knee motion during gait than the control groups. Similarly, Fig. 2 shows that all patient groups except one walked with less knee flexion during the swing phase of gait than the control groups. There were inconsistent findings from the comparison of the maximum angle of knee flexion during stance between patient and control groups, as demonstrated in Fig. 3, yet all studies reported that the patient group walked with a reduced range of flexion during the loading phase of gait (Fig. 4).

Table 3
Summary of outcomes measured

Spatiotemporal	Kinematic	Kinetic
Velocity	Range of motion	GRF F1 (1st vertical maximum)
Stride length	Angle at initial contact	GRF F2 (vertical minimum)
Average step length	Maximum angle during loading	GRF F3 (2nd vertical maximum)
Cadence	Range of motion during loading	GRF F4 (fore-aft shear maximum)
Maximum angular velocity	Maximum angle during stance	GRF F5 (fore-aft shear minimum)
Stance time	Minimum angle during stance	GRF F6 (medio-lateral shear maximum)
Swing/stance ratio	Maximum angle during swing	GRF F7 (medio-lateral shear minimum)
Time of weight acceptance	Minimum angle during swing	No. subjects biphasic sagittal moment pattern
Single limb support time	Maximum adduction angle	Maximum flexion moment
Double limb support time	Maximum abduction angle	Maximum extension moment
Ratio of treated to untreated SLS time	Abd/add and IR/ER range of motion	Maximum adduction moment
Stride time	Angle at maximum angular velocity	Maximum abduction moment
Step time		Maximum IR moment
Maximum step length		Maximum ER moment
Ratio of treated to untreated step length		Maximum extension moment at initial contact
Step width		Maximum extension moment at terminal stance
Step width/height		Maximum flexion moment at pre-swing
Maximum angular velocity		
Time of GRF F3		

GRF, ground reaction force; abd, abduction; IR, internal rotation; add, adduction; ER, external rotation.

3.5.2. Kinetic data

The most commonly reported kinetic analysis as seen in Table 4 was the determination of the proportion of TKR patients that displayed a biphasic sagittal knee moment pattern. A biphasic moment pattern occurs when the initial external moment across the knee tends to extend the knee before rapidly changing to a flexion moment, then changing again to extend the knee and then flex the knee towards the end of stance, as represented by Fig. 5. This biphasic moment pattern is typically associated with normal gait [12,26,27]. Sagittal moment patterns that are not biphasic are usually described as being either a quadriceps avoidance pattern (where an extension moment is present throughout stance) or a quadriceps overuse pattern (where a flexion moment is present throughout stance) [28]. The findings of the five patient groups that were assessed for the presence of a biphasic moment pattern are shown in Table 6. As this table shows, approximately 80% of control subjects demonstrated this biphasic pattern compared to only 20%–36% of TKR patients.

The maximum magnitudes of flexion and extension moments during gait were also reported in most studies. However, further analysis and comparison of results was not possible because effect sizes could be calculated for the results of only one study given the lack of standard deviations reported in the other relevant studies [13–16,24]. Similarly, the vertical ground reaction force was measured by a number of studies but insufficient detail in reporting prevented the valid calculation of effect sizes.

Saari et al. were the only authors to compare the maximum coronal plane knee moments of patients compared to controls [14]. Although no significant difference was reported for any patient group, the lack of analysis in other studies is surprising given the attention that this gait outcome has received in relation to the progression of osteoarthritis and TKR component loosening [29–32].

Electromyographic (EMG) data during gait was collected in four studies [11,13,15,19]. Wilson et al. [13] were the only authors to correlate EMG data with the findings of gait analysis. They reported that TKR patients with an abnormal sagittal knee moment pattern recorded prolonged activity of stance phase quadriceps and preswing hamstrings compared to TKR patients with a normal sagittal knee moment pattern.

4. Discussion

This review showed that TKR patients walked with less total range of knee motion than their control counterparts. Contributing to this reduction in overall motion, TKR patients walked with less knee flexion during the swing phase of gait. The range of flexion during the loading phase of stance was also reduced compared to controls. Consistently large effect sizes across these patient–control comparisons indicated the substantial differences between groups regarding these kinematic gait variables.

Despite the consistency of these findings, their implication for patients is unclear. The available range of knee motion following TKR is considered to be an important determinant of patients' functional abilities post-operatively, particularly for activities involving greater knee flexion [33,34]. However, there appears to be no research that has investigated the relationship between a reduction in knee motion during gait and patients' functional abilities. Additionally, suggestions that the range of knee motion may have implications for the wear of the TKR prosthesis have not been substantiated [35,36]. Future research is needed to assist our understanding of these issues.

The kinetic findings of this systematic review clearly indicate that following TKR, patients walk with a sagittal moment pattern about the knee that is different from controls. Studies that assessed the sagittal knee moment pattern reported that 64% to 80% of patients did not demonstrate the so-called biphasic moment pattern that was seen in over 80% of control subjects. The presence of a moment that was sustained in either a flexion or an extension direction was considered abnormal by all studies.

Whilst an absence of a normal sagittal moment pattern in patients was the most consistent kinetic finding in this

Table 4
Reported outcome measures

	Outcome Measures	PCL-retained TKR vs Normal									PCL-resected TKR vs Normal						PCL unknown		
		Bolanos et al (1998)	Borden et al (1999)α	Borden et al (1999)β	Chen et al (1991)	Fuchs et al (2002)	Fuchs et al (2004)	Saari et al (2005)γ	Saari et al (2005)δ	Simon et al (1983)	Bolanos et al (1998)	Chen et al (1991)	Fuchs et al (2004)	Saari et al (2005)δ	Saari et al (2005)ε	Wilson et al (1996)	Brugioni et al (1990)	Chassin et al (1996)	Smith et al (2004)
Kinematic Parameters	*Range of motion (deg)*	↓	NS	↓		↓					↓					↓			
	Angle flexion at IC (deg)				↓							↓				NS			NS
	Flexion ROM during loading (deg)	↓									↓					↓			↓
	Maximum angle during stance (deg)				↑	NS						↑							↑
	Minimum angle during stance (deg)					NS	NS	NS	↓				NS	NS	NS				NS
	Maximum angle during swing (deg)	↓			↓	NS	NS	NS	NS		↓	↓	NS	NS	↓	↓			↓
	Maximum adduction angle (deg)							↑	NS					NS	NS				
	Maximum abduction angle (deg)							↓	NS					NS	NS				
Kinetic Parameters	*GRF F1 (% body weight)*		NS	↓	↑		NS					↑	NS						
	GRF F2 (% body weight)				↑		NS					↑	NS						
	GRF F3 (% body weight)		NS	NS	NS		NS					↑	NS						
	No. subjects biphasic sagittal moment pattern									↓							↓	↓	↓
	Maximum flexion moment (Nmkg-1 or Nm)	GR	NS	NS				NS	NS		GR			NS	NS	GR	GR		↓
	Maximum extension moment (Nmkg-1 or Nm)	GR	NS	NS				↓	↓		GR			NS	NS	GR	GR		
	Maximum adduction moment (Nmkg-1 or Nm)							NS	NS					NS	NS	GR	GR		
	Maximum abduction moment (Nmkg-1 or Nm)							NS	NS					NS	NS	GR	GR		

PCL posterior cruciate ligament
TKR total knee replacement
NS not statistically significant
GR graphical representation only
(grey) not reported
↓ patient group significantly less than controls
↑ patient group significantly greater than controls

αsimultaenous bilateral TKR
βstaged bilateral TKR
γflat tibial component TKR
δconcave tibial component TKR
εposterior stabilised TKR

ROM range of motion
IC initial contact
abd abduction
add adduction
GRF F1 1st maximum vertical
GRF F2 1st minimum vertical
GRF F3 2nd maximum vertical

literature, little is known about the cause of this phenomenon. It has been suggested that the abnormal pattern relates to the absence of the ACL and a subsequent reduction in knee proprioception, but this remains unsubstantiated [37]. Although there is some evidence to suggest that the abnormal pattern may be a residual characteristic

Table 5
Gait analysis protocols

	Walkway (W) or Treadmill (T)	Walkway Distance (m)	No. Trials Averaged	Kinematic Collection Frequency (Hz)	Kinetic Collection Frequency (Hz)	Knowledge of Forceplate
Bolanos et al (1998)	W	6				
Borden et al (1999)	W	7	3	60	1000	aware
Brugioni et al (1990)	W	10		75		
Chassin et al (1996)	W	10	12	60	120	unaware
Chen et al (1991)	W	10		50	50	
Fuchs et al (2002)	T	8.3	1	100	N/A	N/A
Fuchs et al (2004)	W					
Saari et al (2005)	W		3	240		aware and asked not to target
Simon et al (1983)	W		selected from 3 to 6			
Smith et al (2004)	W		5	50	2000	
Wilson et al (1996)	W		2 (gait cycles within trial averaged)	60	60	

[grey box] not reported
N/A not applicable

of pre-operative gait [12], in the only study in this review to assess gait pre-operatively almost one third of the patients with an abnormal moment pattern post-operatively did not demonstrate this pattern prior to surgery [12]. This suggests that there are other factors contributing to the development of an abnormal sagittal knee moment pattern that require further investigation. It is likely that an abnormal kinetic pattern results in abnormal muscle function as reported by Wilson et al. [13], and it may be of importance in terms of patients' functional abilities, biomechanical effects on other joints, and prosthetic failure. However, as with the interpretation of the kinematic characteristics of gait in TKR patients, the implications of the abnormal moment patterns for patient outcome and function remain unclear.

Interestingly, only one study [14] compared coronal plane kinetic data in patients and controls, despite the potential relevance of this information to the outcome of TKR. Hilding et al. reported that those patients with prostheses that were classified as 'unstable' by roentgen stereophotogrammetry and therefore likely to demonstrate premature component loosening also displayed higher maximum adduction moments during gait [3]. There is sufficient evidence to support the suggestion that coronal moments in

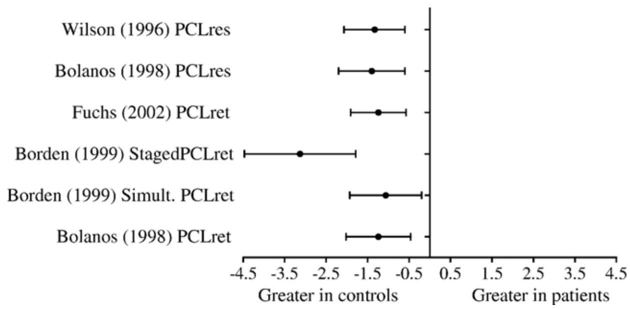

Fig. 1. Effect sizes of patient groups compared to control groups for the total range of knee motion during gait.

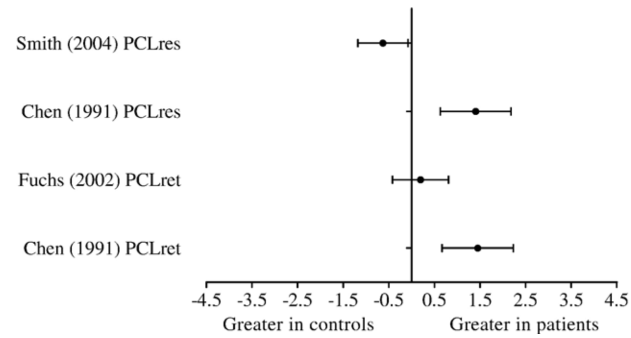

Fig. 3. Effect sizes of patient groups compared to control groups for the maximum knee flexion during stance phase.

TKR patients are related to the prosthetic alignment [38] yet the magnitudes of coronal moments that are potentially detrimental to the prosthesis have not been investigated. The relationship between the alignment of the prosthetic components, coronal plane kinetics, and wear and loosening of TKR prostheses warrants further research.

Cross-study comparison of reported findings was limited to a core set of gait variables for which effect sizes could be calculated for two or more patient groups per prosthetic design. Identification of common trends in other gait variables reported was not plausible given the relatively few studies that reported on each variable with inconsistent findings. For instance, twenty-four of the twenty-nine variables used in the eleven studies in this review were not reported by enough studies or in enough detail to allow useful comparison. This diversity in the selection of outcomes to describe gait following TKR cannot be explained by differences in research objectives of individual studies alone. Such diversity in the reporting of parameters outside this core set suggests that there is a lack of consensus amongst researchers about other aspects of gait that are important when assessing the outcome of TKR. Further characterisation of the implications of gait analysis for clinical practice may assist in identification of the gait characteristics that are potentially more important, thereby allowing for greater cross-study comparison and the synthesis of findings from multiple studies.

Variations in the methodology of gait analysis were identified with regard to the characteristics of the subjects selected for assessment. It has been well established that subject age, gender, height and weight can all affect the results of gait analysis [20–23]. Despite this, only two studies reported that these characteristics were similar in both the patient and control groups. Normalisation of gait data to account for differences in subject height and weight is relatively common in the wider gait literature [39,40] and can minimise the potential confounding of differences in findings that may be due to subject anthropometry. Moisio et al. [40] compared two common techniques and concluded that normalising gait data to bodyweight as a product of height was effective in minimising confounding and was also more likely to reduce differences related to subject gender. In addition, this appears to be the most common normalisation technique in the wider gait literature, and therefore it is recommended that future gait analysis research in patients following TKR should report results normalised to bodyweight and height.

As indicated by the diversity in the studies included in this review, there are many methodological options for researchers to minimise the potential confounding of speed on subject group comparisons. Ideally, walking velocity should be the same between subjects when comparing biomechanics so that any differences identified can more likely be attributed to the variable of interest rather than a difference in speed. However, instructing all or some subjects to walk at pre-determined speeds may elucidate biomechanics that are not representative of subjects' normal gait. Additionally,

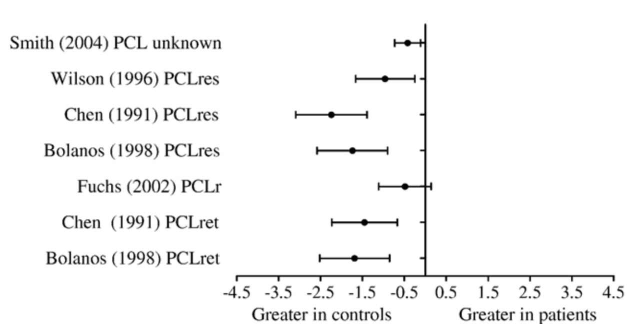

Fig. 2. Effect sizes of patient groups compared to control groups for the maximum knee flexion during swing phase.

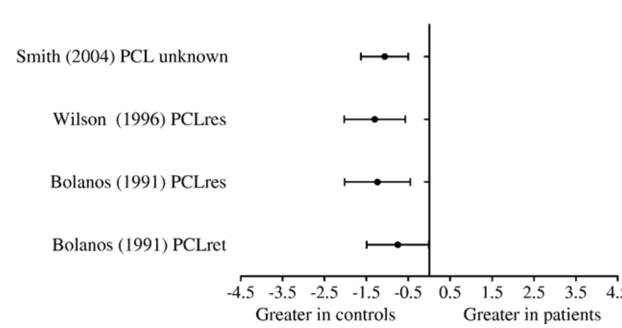

Fig. 4. Effect sizes of patient groups compared to control groups for the range of flexion during loading phase of stance.

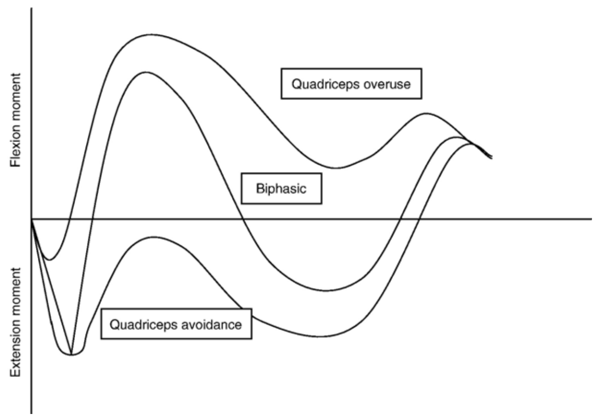

Fig. 5. Graph representing the biphasic, quadriceps overuse and quadriceps avoidance sagittal moment patterns about the knee.

normalisation of walking speed does not account for differences in the magnitude of biomechanical parameters. The issue of accounting for speed is not unique to research in this population and is reflected in other gait literature, but it may be more pertinent in this patient population because of the more common study design to compare subjects to 'normal' controls rather than comparing pre- and post-intervention. It appears that the most common protocol is to record subjects walking at their own pace and to use speed as a covariate when statistical comparisons are made. The authors of this review have certainly adopted this approach. Differences in other aspects of the gait analysis protocols (summarised in Table 5) may also contribute to the variation seen in reported findings, however, insufficient information was provided in most studies, precluding a more in depth analysis.

The inconsistency in findings across the studies may also reflect the variation in selection of patients with bilateral TKR. There is some research indicating that joint replacement may accelerate OA in the contralateral limb, presumably due to altered biomechanics [41]. Indications of similar effects on contralateral knees with TKR have not been investigated. Given the relatively high incidence of bilateral TKR for OA [42], exclusion of these patients in research would extensively limit sample size and subsequently reduce power of any findings. Whilst further research is necessary to clarify the potential differences in biomechanics between patients with unilateral TKR and patients with bilateral TKR, there is not yet sufficient evidence to justify the exclusion of bilateral TKR patients from research considering the limitations caused by excluding these patients.

Substantial differences were also identified in the characteristics of the knee replacement prostheses used in the various studies. There is ongoing discussion in the literature about the biomechanical effects of either retaining or resecting the PCL in TKR [26,43–45]. Other prosthetic characteristics such as the radii of the articulating surfaces, as well as the decision to retain or resurface the patella may also influence biomechanics during gait [46,47]. We were unable to identify any trend in the gait patterns following either PCL resection or retention, compared to controls. Similarly, there was insufficient data to determine gait patterns related to other prosthetic design characteristics. Therefore, it is possible that variation in prosthetic design may contribute to the inconsistency of findings across the different studies.

Several limitations need to be considered when interpreting the findings of this review. A systematic review cannot correct for the biases and methodological flaws present in the original studies. All relevant studies were included in this review regardless of quality so that the methods of gait analysis research could be summarised. It is possible that this review is subject to bias through the inclusion of studies reported in published literature only. Only published studies were included to maximise the availability of the data to all readers. This review did not include studies that compared patients' pre-operative gait with gait following TKR. Pre-operative gait may be important in predicting post-operative gait in this patient group as indicated by Smith et al. [12]. A search of the literature identified an additional nine studies with this pre-post intervention design [3,12,27,44,48–52]. Although all studies reported improvement in patients' gait towards normal following surgery, only two studies

Table 6
Sagittal kinetic pattern findings as a percentage of the subject group

	PCL RETAINED TKA		PCL RESECTED TKA		PCL unknown TKA					
	Simon et al (1983)		Wilson et al (1996)		Brugioni et al (1990)		Chassin et al (1996)		Smith et al (2004)	
	PATIENTS	CONTROLS	PATIENTS	CONTROLS	PATIENTS	CONTROLS	PATIENTS	CONTROLS	PATIENTS	CONTROLS
Biphasic moment pattern	20#	80	25		36	80	23	79	30	95
Quadriceps avoidance pattern	30#	13	31		36	20	31	5	40	
Quadriceps overuse pattern	50#	7	44		28	0	46	16	30	

data reported for only 10 of the 12 patients included in this study. Percentages represent the sample of 10.

(grey shading) not reported

suggested that patients' post-operative gait could be predicted by their pre-operative gait [3,44]. Finally and importantly, the design of TKA prosthetic components continues to evolve. The designs used in this review were of varying ages and it may not be appropriate to apply the knowledge of the biomechanics of these designs to those currently used.

In summary, this review identified several characteristics of sagittal plane kinematics and kinetics in patients following TKA that were consistently different from unimpaired control subjects. However, for most of the reported outcomes, the findings were inconsistent between the studies. This may relate to discrepancies in the research methodologies as well as prosthetic designs. Further research that emphasises the clinical usefulness of findings from gait analysis may assist in determining which of the myriad of gait variables provide the most useful information about the gait of patients following TKA.

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