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Patterns in the knee flexion-extension moment profile during stair ascent and descent in patients with total knee arthroplasty

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ABSTRACT

The aim of this study was to investigate the prevalence of abnormal knee biomechanical patterns in 40 patients with a modern TKA prosthesis, compared to 40 matched control participants when ascending and descending stairs. Fewer patients were able to ascend (65%) or descend stairs (53%) unassisted than controls (83%). Of the participants who could ascend and descend, cluster analysis classified most patients (up to 77%) as demonstrating a similar knee moment pattern as all controls. A small subgroup of patients who completed the tasks did so with distinctly abnormal biomechanics compared to other patients and controls. These findings suggest that recovery of normal stair climbing is possible. However, rehabilitation might be more effective if it were tailored to account for these differences between patients.

1. Introduction

The ability to ascend and descend stairs is a task that is encountered frequently during daily living, particularly as stairs often provide the most convenient access point to buildings and services in the community. Unfortunately, it has been reported that stair climbing is the daily functional activity for which patients with total knee arthroplasty (TKA) are most dissatisfied with their outcome from surgery and there is evidence that stair climbing ability is not improved following TKA, and remains significantly impaired for up to 2 years following surgery (Bourne et al., 2010; Zeni and Snyder-Mackler, 2010b).

Measuring knee biomechanics using motion analysis techniques has the benefit of providing information about the specific challenges faced by patients with TKA when negotiating stairs. Using this approach, the external knee joint flexion–extension moment pattern throughout stair ascent has been assessed in three previous studies (Andriacchi et al., 1982; Andriacchi et al., 1997; Catani et al., 2003). Each of these studies identified a subgroup of patients for whom the knee moment pattern was distinctly different from the other patients, and also from what is typically expected of normal stair ascent (Andriacchi et al., 1982; Andriacchi et al., 1997; Catani et al., 2003).

All authors of the previous studies agreed that design characteristics of some TKA prostheses may contribute to the development of an abnormal moment pattern during stair ascent, and particularly that the abnormal moment profile represented an attempt to avoid generating an external flexion moment (Andriacchi et al., 1982; Andriacchi et al., 1997; Catani et al., 2003). All three authors described a distinctly abnormal moment pattern in 40–60% of the patients. All authors agreed that characteristics of the sagittal moment in this proportion of patients suggested an attempt to avoid generating a knee flexion moment, which also avoided the need for quadriceps activity. Two of these studies were completed more than 20 years ago, and all of these studies assessed only patients with good or excellent outcome from TKA. Without recent studies investigating the profile of the sagittal plane moment it is not known what proportion of patients with modern prostheses may expect to demonstrate abnormal moment patterns, and how the biomechanical characteristics of these patients differ from normal. Therefore, an investigation of a larger cohort that is representative of typical contemporary patients would allow for more detailed description of the biomechanics of stair ascent and descent following TKA.

The demands of descending stairs may be different from stair ascent, as the primary role of the quadriceps during descent is to absorb the force needed to lower bodyweight, rather than generate force for elevation, as in stair ascent. However, despite the potentially greater challenge that stair descent presents, there have been few studies that attempted to describe the biomechanics of patients during stair descent (Andriacchi et al., 1982; Bolanos et al., 1998;

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Catani et al., 2003). None of these studies explored the prevalence of an abnormal pattern of knee moment during stair descent, therefore little is known about how the demand for quadriceps control changes throughout the activity.

The aim of this study was therefore to investigate the prevalence of abnormal knee flexion–extension patterns during both stair ascent and descent in a representative group of patients following TKA with reference to a healthy control group. We hypothesised that most patients with TKA would ascend and descend stairs with knee moments that were similar to people without knee pathology. We also hypothesised that in a smaller proportion of patients the knee moment would be smaller in magnitude and delayed.

2. Materials and methods

All patients who underwent TKA by a single experienced knee surgeon over 2 consecutive years were assessed for eligibility for study inclusion. Patients were invited to participate if they had undergone TKA for osteoarthritis at least twelve months and not more than 18 months earlier and were able to walk 10 metres without a gait aid. Patients with other documented orthopaedic, neurological or visual disturbances that may affect gait, including joint arthroplasties of the hips and ankles were excluded. Within 5 years, up to 30% of patients with primary TKA undergo TKA in the contralateral limb (Australian Orthopaedic Association, 2012; McMahon and Block, 2003; Shakoor et al., 2002). Therefore, to maximise the generalisability of the findings of this study, patients with bilateral knee arthroplasty were included, provided that the most recent procedure was undertaken at least 12 months prior to testing. From an initial list of 78 patients, 22 were excluded because of co-morbidities that may affect gait, nine declined and seven were unable to be contacted. The remaining 40 patients attended the gait laboratory for assessment. All participants had received a fully cemented Genesis-II posterior stabilised prosthesis (Smith and Nephew, Memphis, Tennessee, USA) and the patella was resurfaced in all knees. All participants received standard post-operative care, which emphasised early weightbearing mobility, quadriceps strengthening and maximisation of range of motion. In the 13 participants that had undergone bilateral knee arthroplasty surgery, only the most recent TKA was considered for analysis.

The control group consisted of 40 participants who were assessed for eligibility to participate in the study using the same criteria as the TKA participants, except that control participants were excluded if they had undergone any joint arthroplasty surgery or reported any symptoms of lower limb osteoarthritis. All control participants were matched to the age (± 2 years) and gender of a member of the TKA group. A single limb of each control participant was used in the analysis and was determined by the operated limb of the matched TKA participant.

Ethical approval was granted from the institution's Human Ethics Committee and written informed consent was obtained from all participants.

An eight camera Vicon MX3 Motion Analysis System (Vicon, Oxford, UK) was used to collect kinematic data at a sampling rate of 100 Hz. The gait laboratory consisted of a 10 m walkway with two force plates (Kistler, Switzerland and AMTI, Watertwon, MA, USA) that were embedded into the floor in the middle of the walkway. A two-step staircase with dimensions based on the Building Code of Australia (step height of 180 mm and a step tread of 300 mm) was placed adjacent to these embedded forceplates (Office of the Australian Building and Construction Commissioner, 2006). A third force plate (AMTI, Watertown, MA, USA) was placed on the first step of the staircase so that the kinetic data of three consecutive steps could be collected (two level steps and one elevated step). Only data from this elevated force plate is included in this manuscript. All force plate data were collected at a sampling rate of 4000 Hz.

Thirteen 14 mm diameter reflective markers were placed centrally over the sacrum, and bilaterally over the anterior superior iliac spines, lateral femoral epicondyles, lateral and medial malleoli, calcanei, and second metatarsals. Markers on 5 cm wands were placed on the lateral thighs and legs. A knee alignment device was used to determine the centre of the knee joint during a static data calibration. These marker placements were based on the modified Helen Hayes model (Davis et al., 1991; Kadaba et al., 1989). Additional markers were placed on the iliac crest to allow reconstruction of occluded ASIS markers (McClelland et al., 2010).

During stair ascent, participants were instructed to take two steps on a level walkway before ascending the staircase in a reciprocal footfall pattern. During stair descent, the process was reversed so that participants commenced on the top step, descended onto the first elevated step which included a force plate and descended again to take 2 steps along the level walkway. There were no rails for support on the staircase. Participants were encouraged to practise ascending and descending the staircase as many times as necessary until comfortable with the process. Data collection did not proceed if patients were unable to ascend or descend without support, or were unable to ascend or descend with reciprocal footsteps. Participants were asked to ascend and descend the staircase until a minimum of three and a maximum of five trials of data were collected from each limb.

Patients were assessed using the American Knee Society Knee Score (KSS) at a routine 12 month post-operative follow-up visit with the surgeon (Insall et al., 1989). At the time of motion analysis testing, patients with TKA also completed the Total Knee Function Questionnaire (TKFQ), which collects information about patients' perceived functional abilities and their importance to daily life (Weiss et al., 2002). Responses relevant to overall satisfaction and stair climbing were included in this study.

Vicon PlugIn Gait (Vicon, Oxford Metrics, Oxford, UK) software was used to estimate lower limb joint positions, based on the model proposed by Davis et al. (1991) and Kadaba et al. (1989). Joint kinematics were calculated using Euler angles (flexion/extension, abduction/adduction, and internal/external rotation). Joint moments were calculated using standard inverse dynamics from force vectors that were defined in a global coordinate system and projected to a local coordinate system of the rigid body segment distal to each joint. The moments referred to throughout this manuscript are external to the knee and normalised to bodyweight and height.

A single step cycle from each trial was included for analysis and was time normalised to 100% of the step cycle. During stair ascent, initial contact onto the first elevated step was considered as the beginning of the step cycle (0%) and toe-off of the same foot as the end of the step cycle (100%). During stair descent, initial contact onto the first elevated step was considered as the beginning of the step cycle (0%) and toe-off of the same foot was defined as the end of the step cycle (100%).

Knee flexion angles and moments in the sagittal plane were calculated for each trial of each participant. Key biomechanical variables were identified and averaged across all trials of each individual (Fig. 1). For stair ascent, these were the maximum knee flexion angle (degrees), the maximum knee flexion moment (%Bw-Ht) and the time when the sagittal moment changed direction from flexion to extension (% of step cycle) (Fig. 1). For stair descent, these were the maximum knee flexion angle during loading phase (0–50% of the step cycle as bodyweight is accepted onto the limb) (deg), the time when the sagittal moment changed direction from extension to flexion (% of step cycle), the maximum knee flexion moment during loading (% Bw-Ht), the maximum knee flexion moment during late stance phase (50–100% of the step cycle, %Bw-Ht) and the time taken to complete each task (s).

Hierarchical cluster analysis was used to identify subgroups of patients using characteristics of the sagittal moment profile. Two separate cluster analyses were performed in this study: (i) a single analysis to classify moment profiles of all control and TKA participants who completed the stair ascent task ($n=59$) and (ii) a single analysis to classify moment profiles of all control and TKA participants who completed stair descent ($n=54$). The hierarchical cluster analysis procedure (based on the method described by Ward (1963)) begins by assigning each case to its own cluster. There is then a stepwise process whereby moment profiles that are most similar are joined to form clusters. This process continues until a single cluster is formed in a hierarchical tree (dendogram). In this study, the similarity between gait profiles was determined by the squared Euclidean distance between profiles and by using a between-groups linkage (the average similarity within a cluster is calculated and the case with the distance most similar to the average is the next to join the cluster). Two distinct waveforms of the sagittal moment profile have been described in patients with TKA during a stair ascent task (Andriacchi et al., 1982; Andriacchi et al., 1997; Catani et al., 2003), therefore it was determined *a priori* that there would be two clusters in each analysis based on key characteristics of this moment. In these studies, abnormal stair ascent has been described as an apparent avoidance of quadriceps use, which was characterised by a reduction in the maximum external flexion moment, and reduced time during stance that the quadriceps were required (i.e. reduced time that the external moment was in a flexion direction). Therefore, in the cluster analysis of stair ascent the independent variables were determined *a priori* as (i) the magnitude of the maximum flexion moment and (ii) the percentage of the gait cycle where the knee flexion moment changed direction to become a knee extensor moment (Fig. 1C). Patterns of the sagittal moment have not been described during stair descent where the primary role of the quadriceps is to control lowering of bodyweight onto the descended step. An avoidance of demand for quadriceps control during this moment is likely to be reflected in a reduction of the maximum flexion moment and a delay in the need for quadriceps activity (i.e. delay in generation of a flexion moment). Therefore in cluster analysis of stair decent, the independent variables were defined *a priori* as (i) the magnitude of the maximum knee flexion moment and (ii) the percentage of the gait cycle where the initial knee extensor moment changed direction to become a knee flexor moment (Fig. 1D).

Step-wise discriminant function analysis was used to evaluate the robustness of group allocation, and to evaluate the relative importance of each variable in determining the clusters. In this procedure the discriminant function is recalculated for all except one case. This model is then applied to the withheld case to assign group membership, and the process repeated until each case has been left out. Group assignment is considered robust if there are a high percentage of participants classified to the correct group (i.e. low misclassification rate). This process is similar to that described by Toro et al. (2007) and Mulroy et al. (2003).

Key biomechanical characteristics during both stair ascent and descent were compared between groups, and between clusters using independent samples *t*-tests with $p<0.05$. For all biomechanical parameters reported in this manuscript,