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Altered joint moment strategy during stair walking in diabetes patients with and without peripheral neuropathy

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ABSTRACT

Aim: To investigate lower limb biomechanical strategy during stair walking in patients with diabetes and patients with diabetic peripheral neuropathy, a population known to exhibit lower limb muscular weakness.

Methods: The peak lower limb joint moments of twenty-two patients with diabetic peripheral neuropathy and thirty-nine patients with diabetes and no neuropathy were compared during ascent and descent of a staircase to thirty-two healthy controls. Fifty-nine of the ninety-four participants also performed assessment of their maximum isokinetic ankle and knee joint moment (muscle strength) to assess the level of peak joint moments during the stair task relative to their maximal joint moment-generating capabilities (operating strengths).

Results: Both patient groups ascended and descended stairs slower than controls ($p < 0.05$). Peak joint moments in patients with diabetic peripheral neuropathy were lower ($p < 0.05$) at the ankle and knee during stair ascent, and knee only during stair descent compared to controls. Ankle and knee muscle strength values were lower ($p < 0.05$) in patients with diabetic peripheral neuropathy compared to controls, and lower at knee only in patients without neuropathy. Operating strengths were higher ($p < 0.05$) at the ankle and knee in patients with neuropathy during stair descent compared to the controls, but not during stair ascent.

Conclusion: Patients with diabetic peripheral neuropathy walk slower to alter gait strategy during stair walking and account for lower-limb muscular weakness, but still exhibit heightened operating strengths during stair descent, which may impact upon fatigue and the ability to recover a safe stance following postural instability.

1. Introduction

Diabetes and associated comorbidities have been shown to negatively impact upon locomotion: affecting both gait and balance [1,2]. Diabetic peripheral neuropathy is one of the most common comorbidities known to influence gait [3–5], with diminished foot sensation and progressive muscle weakness placing individuals at a higher risk of falls than their non-neuropathic counterparts [6–8].

Previous studies have investigated the kinetics and kinematics of walking on level ground in patients with diabetes, demonstrating alterations such as smaller step lengths, lower gait speeds [9,10] and lower peak joint moments [11,12] than non-diabetic controls. These gait alterations have been shown to be modulated by the difficulty of the task, with greater effects when walking on uneven surfaces [13]. Our understanding of how people with diabetes negotiate stairs is currently very sparse, despite the higher muscular demands of this task compared to level walking [14,15] and high risk of falling during stair negotiation [16,17]. Picon et al. [18] reported lower ankle and knee joint moments when stepping from stairs to floor, however this transitional step whilst more challenging than level walking, requires lower joint ranges of motion than a step both preceded and followed by an additional step down, which may result in

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lower joint moment requirements for this final step. Therefore, the joint moment strategy of negotiating continuous stairs in patients with diabetes remains unknown. Rate of joint moment production during stair ascent and descent, has been investigated and patients with diabetic peripheral neuropathy were shown to generate joint moments upon initial contact slower, in both stair ascent and descent [19]. Whilst a slower rate of joint moment production has been associated with impaired balance [20], it tells us little of the magnitude of lower limb joint moments developed during these activities.

Elderly populations have been more thoroughly investigated already during stair walking, and have shown similarities to diabetic populations in level walking studies, including slower walking speeds and shorter step lengths [21] as well as decreased muscle joint strengths [22]. Elderly people have been shown to ascend and descent stairs with lower joint moments, but at higher levels of their maximal joint moment-generating capabilities [23,24]. It has been hypothesised that operating at a higher level of their maximal capabilities may explain why the elderly have difficulties completing daily activities [25,26]. If these findings translate to a population with diabetes during stair walking, as indications of such a trend have already been seen during level walking [27], it may highlight the potential utility of exercise interventions for redressing this detrimental effect of diabetes and peripheral neuropathy and improve patients ability to perform daily activities. Therefore, whilst strides toward assessing the musculoskeletal alterations of patients with diabetes during stair walking have begun to be addressed within the past few years, there is still a large knowledge gap presented by the limited number of variables reported and potential ambiguity of the actual activities reported. This study aimed to investigate biomechanical alterations to joint moments during stair ascent and stair descent, as a result of the muscular joint weakness known to occur in populations with diabetes. It was hypothesised that patients with diabetes would adopt a strategy that reduced peak joint moments to maintain magnitudes further within their maximal capabilities.

2. Methods

2.1. Participants

Power analysis identified minimum group sizes of $n = 18$, for an effect size 0.657 ($\beta = 0.1$, $\alpha = 1\%$). Power analysis was based upon one of the key variables, ankle joint moment, conservative population standard deviations (0.18 Nm kg^{-1}) and a between group difference to be considered significant (0.29 Nm kg^{-1}) based upon previous work on stair negotiation in older adults [23,24].

After receiving ethical approval from the National Health Service (NHS) ethics committee, as well as the relevant Hospital and University bodies; ninety-four participants gave informed written consent: sixty-one patients with diabetes and thirty-two non-diabetic controls (CTRL group). Participants were assessed to confirm absence of: musculoskeletal disorders, serious foot deformity (e.g. Charcot), open foot ulcers, lower-limb amputation, history of cerebral injury, an inability to walk unaided, or poor visual acuity (less than 6/18 of any aetiology). Absence of diabetes in non-diabetic controls was confirmed by a random blood glucose test (all readings were between 4 and 7 mmol l^{-1}).

Presence of diabetic peripheral neuropathy was assessed for using the modified Neuropathy Disability Score (mNDS) and Vibration Perception Threshold (VPT). Patients were sub sequentially assigned to either the DM group ($n = 39$; mNDS <6 and a VPT <25 for both feet) or DPN group ($n = 22$; mNDS score ≥ 6, and/or a VPT ≥ 25 V on either or both feet) group.

2.2. Gait analysis

Participant's gait was assessed during ascent and descent of a 7-step staircase (Fig. 1) in a step-over-step manner (one foot per step) at their self-selected speed. Participants were provided with tight-fitting shorts and t-shirts for the gait analysis, and standardised footwear with a neutral foot bed (MedSurg, Darco, Raisting, Germany) to ensure standardisation of footwear, whilst maintaining a suitable shoe for the high-risk (ulceration) feet of the diabetic participants. For safety, all participants wore a full-body harness during gait analysis.

Kinematics were measured using a ten-camera Vicon (Vicon, Oxford, UK) system, and a fifty-six retroreflective marker modified Helen-Hayes whole-body marker set. Modifications to the marker set included two additional tracking markers on each foot and shank, and three additional tracking markers on the pelvis, to provide redundancy for any marker dropout due to occlusion by the staircase structure. Medial ankle and knee markers were also added to improve joint centre definition for those joints. Joint centres were defined using medial and lateral joint markers for the ankle and knee, and hip joint centres were calculated based upon the Bell, Pederson and Brand hip joint regression equations [28]. Kinetics were recorded from four Kistler force platforms (Kistler, Winterthur, Switzerland) mounted in steps 2–5 of the seven-step staircase.

Participants were asked to ascend and descend the staircase at their self-selected speed until a minimum of 3 trials were collected for both ascent and descent. Adequate rest was provided between trials to minimise the impact of fatigue. Gait velocity was calculated for each trial and lower-limb joint moments were calculated using inverse dynamics. Peak joint moments were defined as the peak during the stance phase.

2.3. Maximum isokinetic joint moment

Maximum effort concentric (muscle shortening) and eccentric (muscle lengthening) ankle plantarflexion and knee extension moments were measured using an isokinetic dynamometer (Cybex Norm, USA) as previously described and performed by the same cohort [27]. Due to patient availability, maximum isokinetic joint moment were recorded for fifty-nine (CTRL: $n = 18$, DM: $n = 27$ and DPN: $n = 14$) of the original ninety-four participants. These muscle groups were chosen as the predominant muscle groups active

Fig. 1. Experimental seven-step staircase with four Kistler force plates built into steps 2–5. A moveable dolly mounted on the ceiling above the staircase allowed a safety harness to be used whilst participants walked along the staircase.

during stair ascent and stair descent. Each joint was assessed at a range of angular velocities ($60^\circ s^{-1}$, $120^\circ s^{-1}$, $180^\circ s^{-1}$ and $240^\circ s^{-1}$) to represent the range of angular velocities expected at these joints during stair negotiation. The order of joints and angular velocities tested was randomised for each participant, and participants performed 3 trials of each condition from which the peak value was selected. All performed knee extension tests in a seated position with the hip flexed at 85° (0° = supine position), and ankle plantarflexion contractions whilst lying prone with the knee in full extension.

2.4. Operating strengths

'Operating strengths' were defined as the ratio of the peak joint moments generated during stair ascent and descent to the maximum isokinetic joint moment, to represent the level of each participant's maximal muscular ability being utilised during the tasks. Each ratio was calculated using the result of the maximum isokinetic joint moment measurement where conditions were matched for muscle action (concentric or eccentric) and at the closest joint angular velocity compared to the angular velocity at the instant of the joint moment peak during gait.

2.5. Statistical analysis

All gait variables were assessed as a mean across the three trials for each activity. Each trial provided four stance periods (two from each limb) upon the force plates; resulting in a mean of twelve values for each participant per activity to minimise the effects of natural within-participant variability. Kinetic variables (peak joint moments and joint work) were normalised to individual body mass and peak joint moments were measured for the loading (weight acceptance, 0–50% stance) and unloading (weight off-loading, 50–100% stance) periods of stance. All variables were analysed using a one-way analysis of variance. Due to differences in velocity between groups, gait variables were also tested using an analysis of covariance with velocity as the covariate. Bonferroni post hoc tests were utilised to assess differences between groups.

3. Results

3.1. Clinical assessment

Patients in the DPN group were heavier than the CTRL and DM groups (+24% and +18% respectively, Table 1). In line with the selection criteria, the neuropathy measures of NDS and VPT scores were also significantly higher in the DPN group relative to the CTRL and DM groups (Table 1), but no difference between CTRL and DM groups. The DM group was also statistically similar to the CTRL group for age, body mass, height and BMI (Table 1).

Table 1
Clinical measurements for the controls (CTRL: $n = 32$), diabetic patients with no neuropathy (DM: $n = 39$) and diabetic patients with diabetic peripheral neuropathy (DPN: $n = 22$). Values are means (standard error).

Variable	Group mean (standard error)		
	CTRL	DM	DPN
Age (years)	53 (3)	56 (2)	57 (2)
Body mass (kg)	75 (2)	78 (2)	93 (5)[c,d]
Height (m)	1.7 (0.02)	1.68 (0.02)	1.72 (0.09)
BMI ($kg\,m^{-2}$)	26 (1)	28 (1)	31 (1)[c,d]
NDS (Score/10)	1 (0.2)	1.6 (0.3)	7 (1)[c,d]
VPT (Volts)	8 (1)	10 (1)	30 (2)[c,d]

[c] Significant ($p < 0.05$) difference from the controls.
[d] Significant ($p < 0.05$) difference from the DM group.

3.2. Maximum isokinetic joint moments

Maximum isokinetic joint moments were recorded for 59 of the original 94 participants (CTRL: $n = 18$, DM: $n = 27$ and DPN: $n = 14$). Both DM and DPN groups showed lower maximum isokinetic joint moments than the CTRL group at both ankle (eccentric: −27% and −39%; concentric: −23% and −33% for DM and DPN vs. CTRLs respectively; for $120^\circ s^{-1}$, Table 2) and knee (eccentric: −35% and −44%; concentric: −23% and −33% for DM and DPN vs. CTRLs respectively; for $120^\circ s^{-1}$, Table 2). Details of maximum isokinetic moments at all recorded joint angular velocities can be found in supplementary Table 1.

3.3. Stair ascent

The DPN group ascended the staircase slower than either CTRLs or DM groups, with no statistical difference between the DM and CTRL groups.

Joint moment profiles for each of the three joints are shown for ankle, knee and hip in Fig. 2. Both DM and DPN groups showed significantly lower peak knee joint moments than the CTRL group (Table 3), which could not be explained by the differences in gait velocity, with the exception of the peak knee joint moment during loading in the DPN group.

During stair ascent there were no significant differences in operating strengths between the groups (Table 3).

3.4. Stair descent

The DPN group descended the staircase slower than the CTRLs, no significant differences in gait velocity were seen for the DM group compared to either other group (Table 3).

Joint moment profiles during stair descent are shown for ankle, knee and hip in Fig. 2. Peak knee joint moments were lower in both DM and DPN groups compared to the CTRL group (Table 3), and remained significant after adjustment for velocity effects, with the exception of loading peak in the DPN group.

During stair descent, ankle operating strengths in the DPN group during loading and unloading were higher than those of the CTRL group (Table 3). Knee operating strengths during unloading, were higher in the DPN group than the CTRLs (Table 3), although like the ankle operating strength during unloading, both only showed significant between group differences once adjusting for the effects of velocity. The DM group only showed significant differences from the CTRL group at the ankle during loading (Table 3).

4. Discussion

This study established a reduced muscle strength in patients with diabetes in line with previous findings within this population [29,30], with the most pronounced weakness in patients with

Table 2
Maximum isokinetic joint moments at $120^\circ s^{-1}$ for controls (CTRL: $n = 18$), diabetic patients with no neuropathy (DM: $n = 27$) and diabetic patients with diabetic peripheral neuropathy (DPN: $n = 14$). Values are means (standard error).

Variable	Group mean (standard error)		
	CTRL	DM	DPN
Max. isokinetic joint moment ($Nm\,kg^{-1}$)			
Eccentric ankle	1.49 (0.13)	1.08 (0.07)[c]	0.9 (0.14)[c]
Concentric ankle	2.44 (0.14)	1.86 (0.09)[c]	1.63 (0.18)[c]
Eccentric knee	1.65 (0.12)	1.07 (0.06)[c]	0.92 (0.12)[c]
Concentric knee	2.7 (0.15)	2.07 (0.1)[c]	1.79 (0.17)[c]

[c] Significant ($p < 0.05$) difference from the controls.

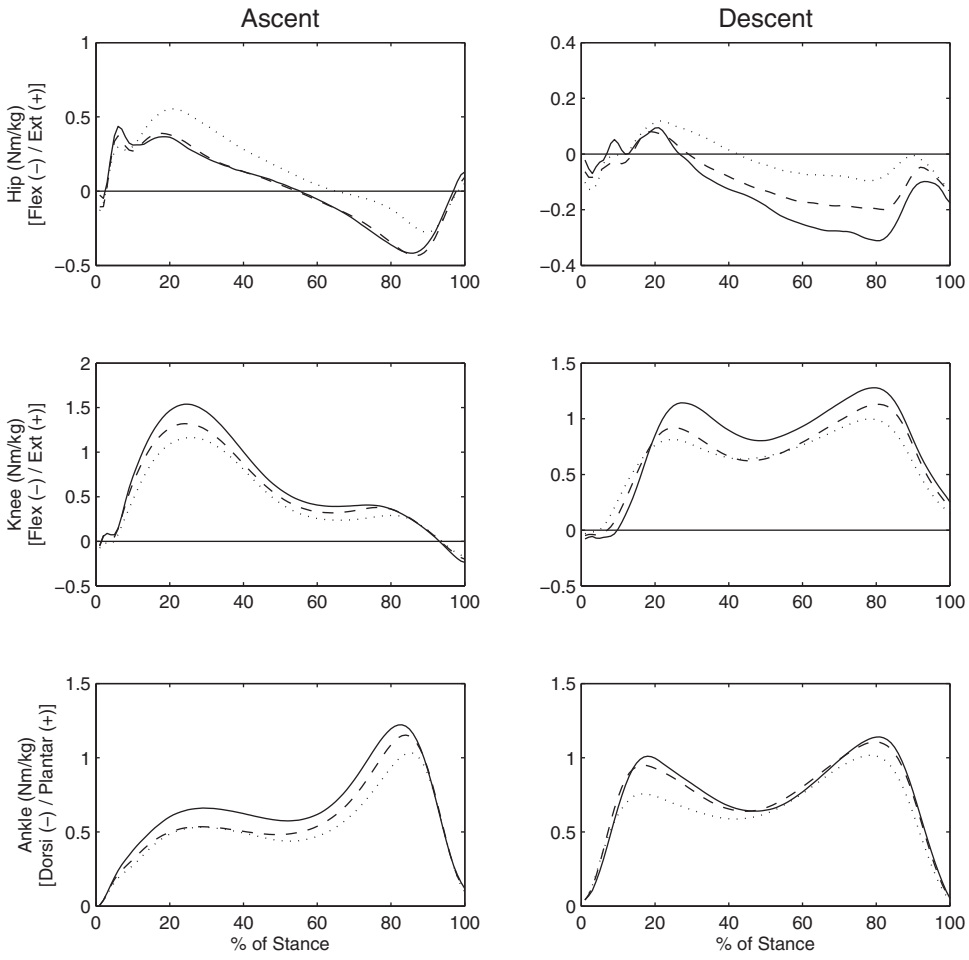

Fig. 2. Moment/time curves during stair ascent and stair descent. Times are normalised to stance phase (0–100%), joint moments are normalised to body mass (Nm kg^{-1}). Solid line – non-diabetic controls (CTRL), dashed line – diabetic patients and no peripheral neuropathy (DM), dotted line – diabetic patients and peripheral neuropathy (DPN).

diabetic peripheral neuropathy. We also showed lower ankle and knee joint moments during stair walking in patients with diabetes both with and without neuropathy compared to healthy controls. The differences from the controls were greatest at the knee, and in the patients with diabetic peripheral neuropathy. Patients with diabetes without neuropathy demonstrated significant differences from the controls at the knee only. However, the non-significant differences in this patient group were in the same direction with those in patients with neuropathy. These findings indicate that peripheral neuropathy has a key influence upon the differences observed. However, the similar neuropathy scores between patients without neuropathy and non-diabetic controls also indicate that, as previously noted in level walking [13,31], gait alterations are not solely a result of diabetic neuropathy.

At the ankle, significantly lower peak joint moments were only observed in the unloading phase of stair ascent for patients with diabetic peripheral neuropathy compared to the non-diabetic controls. In comparison, the knee showed significantly lower joint moments relative to non-diabetic controls in patients both with and without neuropathy, during both activities. This notable difference between ankle and knee may be associated with the greater differences in maximal isokinetic joint moment at the knee compared to the ankle (average differences between DPN and CTRL: ankle 32% lower, knee 37% lower). This greater deficiency in strength seen at the knee relative to the ankle is in contrast to the distal-to-proximal progression typical of diabetic peripheral neuropathy. It should be noted however, that diabetes itself can have an impact upon muscle strength, independent of neuropathies [30,32,33]. Whilst no significant differences were observed at the hip between either patient group and the non-diabetic controls, patients without neuropathy exhibited a lower hip extension moment during stair ascent than the patients with neuropathy (who were similar to the non-diabetic controls). This is the only instance within the findings of this study where the patients without neuropathy exhibited a different manner of gait strategy to the patients with neuropathy and is possibly a response to the greater deficiencies at the knee in patients with diabetic neuropathy. During stair ascent hip extension and knee extension are responsible for accepting the weight of the body and lifting the body onto the step. Given the greater strength deficit at the knee in patients with diabetic peripheral neuropathy than those without neuropathy, patients with more advanced muscle weakness may meet the demands of the task by increasing the workload of the hip due to the lower magnitude of the moments required at hip compared to the knee (e.g. hip: 0.64 Nm kg^{-1}, knee: 1.57 Nm kg^{-1}, example taken as CTRL group during stair ascent; Table 3).

During stair descent, operating strengths were significantly higher for patients with diabetic peripheral neuropathy than non-diabetic controls. These findings coincide with previous findings of higher operating strengths in an elderly population than younger controls during stair descent [24], despite lower peak joint moments in the stair task. During stair ascent no differences were seen in operating strengths between groups, indicating patients were more capable of operating at a similar level to non-diabetic

Table 3
Gait variables during stair ascent and descent. Data shown for controls (CTRL: $n = 18$), diabetic patients with no neuropathy (DM: $n = 27$) and diabetic patients with diabetic peripheral neuropathy (DPN: $n = 14$). Values are means (standard deviation). Covariate effects reported by the ANCOVA are indicated velocity by a "V". Statistical significance between groups is shown after the means and (standard error) in superscript: lowercase "c" and "d" denotes a significant ($p < 0.05$) difference from the CTRL and DM groups (respectively) for the ANOVA, uppercase "C" and "D" denotes a significant ($p < 0.05$) difference from the CTRL and DM groups (respectively) for the ANCOVA using gait velocity as a covariate.

Variable	Covariate effects	Group mean (standard error)		
		CTRL	DM	DPN
Stair ascent				
Temporal spatial				
Velocity ($m\,s^{-1}$)		0.48 (0.01)	0.44 (0.01)	0.39 (0.02)^{cd}
Peak joint moments ($Nm\,kg^{-1}$)				
Ankle loading	V	0.73 (0.06)	0.62 (0.04)	0.61 (0.07)
Ankle unloading	V	1.28 (0.04)	1.18 (0.03)	1.12 (0.05)^{c}
Knee loading		1.57 (0.06)	1.36 (0.04)^{cC}	1.25 (0.06)^{cC}
Knee unloading		0.76 (0.07)	0.57 (0.06)	0.34 (0.06)^{cC}
Hip flexion	V	0.44 (0.03)	0.48 (0.03)	0.37 (0.04)
Hip extension	V	0.64 (0.03)	0.56 (0.03)	0.66 (0.04)^{D}
Operating strength (%)				
Ankle loading		0.6 (0.14)	0.71 (0.1)	0.68 (0.08)
Ankle unloading	V	0.91 (0.17)	1.18 (0.11)	1.45 (0.19)
Knee loading	V	1.01 (0.11)	1.27 (0.14)	1.53 (0.24)
Knee unloading		0.74 (0.22)	0.62 (0.07)	0.69 (0.16)
Stair descent				
Temporal spatial				
Velocity ($m\,s^{-1}$)		0.53 (0.02)	0.47 (0.02)	0.42 (0.03)^{c}
Peak joint moments ($Nm\,kg^{-1}$)				
Ankle loading	V	1.07 (0.06)	1.04 (0.04)	0.94 (0.07)
Ankle unloading		1.2 (0.04)	1.14 (0.02)	1.08 (0.05)
Knee loading	V	1.26 (0.05)	1.01 (0.05)^{cC}	1 (0.07)^{c}
Knee unloading		1.35 (0.07)	1.16 (0.03)^{cC}	1.06 (0.05)^{cC}
Hip flexion	V	0.42 (0.03)	0.36 (0.02)	0.35 (0.03)
Hip extension		0.39 (0.05)	0.27 (0.02)	0.32 (0.05)
Operating strength (%)				
Ankle loading		0.65 (0.07)	1.03 (0.08)^{cC}	1.12 (0.14)^{cC}
Ankle unloading	V	0.81 (0.06)	1.25 (0.14)	1.57 (0.25)^{c}
Knee loading		0.89 (0.08)	1.11 (0.12)	1.42 (0.24)
Knee unloading	V	0.79 (0.04)	1.13 (0.09)	1.45 (0.26)^{c}

controls, although non-significant trends toward heightened operating strengths were still present (stair descent: operating strengths average 45% higher DPN vs. CTRLs, $p < 0.05$; stair ascent: operating strengths 35% higher DPN vs. CTRLs, $p > 0.05$). We recently reported similar alterations in operating strengths in patients with diabetes during level walking [27]; both during level and stair walking patients display higher operating strengths in spite of lower peak joint moments than controls. Higher operating strengths during daily activities have potential implications upon an individual's ability to safely perform these activities.

Patients with no neuropathy have shown fewer statistical differences from non-diabetic controls than patients with neuropathy for all variables. For operating strengths, only the ankle, during stair descent, showed statistical difference between patients without neuropathy and non-diabetic controls. Whilst there were consistent trends of lower joint moments, lower maximal isokinetic joint moments, and higher operating strengths in both patient groups compared to non-diabetic controls; the extent of the differences is lesser within the patients without neuropathy. This indicates that differences in walking strategy on stairs in patients with diabetes is caused by multiple factors, rather than neuropathy alone. However, without the presence of neuropathy, alterations to walking strategy are less pronounced.

In the present study the patients with diabetic peripheral neuropathy, demonstrated a slower gait velocity during both stair ascent and stair descent than non-diabetic controls. During level walking, slower walking speeds are known to reduce joint moments [34]; therefore the impact of velocity as a covariate was assessed. During stair descent, the group effects were seen in ankle and knee operating strengths during unloading. However, a slower gait velocity and the associated lower joint moments should create an expectation of lower rather than higher operating strengths. The opposite presented here, indicating a relationship with the maximum isokinetic joint moments and slower gait velocity, is in line with findings of level walking [34] where self-selected walking speed correlated with lower-limb joint strength. Velocity effects can be seen on a number of the variables assessed here, highlighting the importance of slower speeds as a coping mechanism in patients with diabetes, however, some of the changes to gait strategy showed no velocity effect, indicating strategies other than just walking slower are being utilised in order to lower joint moments.

4.1. Limitations

Although joint moments were normalised to body mass, it should be noted that the DPN group was heavier, with a higher BMI than the DM and CTRL groups, and these variables have been previously shown to be associated with lower gait velocity [35,36]. However, when walking at standardised speeds, extremes in body mass have been shown to produce comparable joint moments during level walking [37]. Whilst the vertical motion of stair walking may suggest a need for higher joint moments in heavier individuals not necessarily present during level walking, the results presented here show lower joint moments in the heavier group. Therefore, we may remain confident in the between group differences shown, as whilst variables may be influenced by weight, the differences seen here cannot be explained by body mass differences alone.

5. Conclusion

We have demonstrated that patients with diabetes and particularly patients with diabetic peripheral neuropathy, exhibit lower lower-limb muscular capabilities and ascend and descent stairs more slowly than healthy controls. We have also shown that patients with neuropathy alter gait strategy to lower peak knee joint moments, which cannot be fully explained by the slower gait velocity adopted. Despite this however, during stair descent patients with diabetic peripheral neuropathy still operate at a higher level of their maximal joint moment-generating capabilities at the knee, which may have implications for adequately responding to perturbations in balance.

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Conflict of interest statement: The authors confirm that they do not have any financial or personal relationships with other people or organisations that could inappropriately influence this manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2016.03.007.

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