A faster walking speed is important for improving biomechanical function and walking performance in stroke survivors

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Conflict of Interest Disclosure: None

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Running title: The need for speed after stroke

Abstract

This study compared joint kinematics and kinetics of young stroke survivors who walk <0.79m/s (slow) or >0.80m/s (fast) with reference to a healthy able-bodied group and provides clinical recommendations for guiding the gait rehabilitation of stroke survivors. Twenty-two young stroke survivors (18-55years) were recruited from 6 hospital sites in the United Kingdom. Stroke participants were classified by walking speed as slow (<0.79) or fast (>0.80m/s) and joint kinematics and kinetics at the pelvis, hip, knee, and ankle were measured during walking on level ground at self-selected speed. Ten walking biomechanical parameters correlated to walking speed ($\rho \geq 0.550$). Stroke survivors in the slow group walked with significantly greater range of sagittal plane pelvic motion ($p<0.009$), reduced range of hip adduction and abduction ($p<0.011$), smaller peak hip extension angle ($p<0.011$) and hip flexion moment ($p<0.029$) for the paretic limb. For the non-paretic limb, a significantly reduced hip flexion moment ($p<0.040$) compared to the fast group and control. We are the first to report how biomechanical function during walking is compromised in young stroke survivors classified by walking speed as slow (<0.79m/s) or fast (>0.80m/s) and propose these biomechanical parameters be used to inform rehabilitation programmes to improve walking for stroke survivors.

Key Words: stroke, young adult, biomechanics, walking speed, gait

Word count (main text): 3888

Tables 3

Figures 2 (4 provided online only)

Introduction

Deriving a consensus on how gait is affected after a stroke is challenging because a stroke affects people differently. It is often dependent on the type, location, size and volume of lesion, age of patient, previous activity levels, health status, and additional co-morbidities (e.g., diabetes). Collating that information alongside biomechanical data can be a challenge. Many studies have provided detailed biomechanical analyses of stroke-affected gait, albeit with varying focal points and methodologies and therefore it is challenging to ascertain which parameters are important or clinically meaningful and should be used to drive future rehabilitation intervention [1-16].

Most studies measuring gait or walking performance of stroke survivors often only include those who are highly functional and able to walk relatively well[10,17]. This is because data collection on less able participants is challenging and shows high within-group variance. The data can be of poorer quality due to logistical difficulties of collecting the data. For example, it can be difficult to capture biomechanical data as it often requires multiple walking trials up and down a gait laboratory or walking on a treadmill. Some participants may find it challenging to walk unassisted for that duration due to muscle weakness, spasticity, cognitive challenges, and risk of falling[18]. Therefore, there is a danger of excluding less functional stroke survivors when measuring walking performance or opting for less demanding simpler clinical tests (e.g., 10 metre walk test) which do not capture the nuances of gait deviations post-stroke.

Many studies present biomechanical data on stroke survivors, but the vast majority is very limited, reporting only movement in the sagittal plane, one joint, one phase of the gait cycle, or temporal and spatial parameters (e.g., stride length, step length)[1,4-6,15,16,19-25]. The focus on sagittal plane kinematics and kinetics is justified because movement in this plane is in the direction of travel and therefore of greatest magnitude. However, abnormal or compromised movement may occur in all planes, thereby highlighting the need for joint kinematics and kinetics evaluations in multiple planes, and across the entire gait cycle.

Walking speed is routinely used to predict recovery and as a surrogate measure of function after stroke[10,26,27] and other conditions[28,29]. However, previous studies [1,4,17,19,30,31] report considerable inter-participant variation in walking speed post-stroke. Although, participants in those studies walked at varying speeds, they were grouped together, and it is difficult to determine whether/how their walking biomechanics were also different and how it affected walking speed[32-34]. Perry et al[35] seminal work proposed four categories of ambulation ability after stroke according to walking speed. Those who walk slower than 0.42m/s are confined to indoor walking only, 0.42- 0.79m/s are predicted to have difficulty walking outdoors, 0.80- 1.2m/s are able to walk outdoors but slower, and finally those who walk faster than 1.2m/s are considered similar to the able-bodied. By grouping participants according to walking speed (e.g., via Perry et al[35] defined groups) this may provide key inferences for how gait has changed post-stroke, and how to improve walking performance with targeted rehabilitation driven by biomechanical function.

The vast majority of previous gait research in stroke survivors includes older participants and they may walk differently due to age related neuromuscular and musculoskeletal changes because of older age, rather than just due to the stroke[10,11,17]. Identifying what changes are a result of the stroke rather than ageing is key to understanding gait after stroke and for developing future rehabilitation interventions to improve gait function. One strategy could be to include stroke survivors who are younger (i.e., less than 55years) as they are less likely to demonstrate musculoskeletal and cognitive changes associated with ageing, so the changes associated with stroke are more apparent.

The aims of this study are to a) determine which walking biomechanical parameters correlate to walking speed in young stroke survivors in order to provide benchmark parameters that are affected post-stroke, b) To compare joint kinematics and kinetics of young stroke survivors who walk slower than 0.79m/s (a slow group) to those who walk faster than 0.80m/s (a fast group) and with reference to a healthy able-bodied control population c) Provide clinical recommendations for guiding the gait rehabilitation of young stroke survivors. We hypothesised that key sagittal plane kinetic and kinematic variables will correlate with walking speed.

Methods

Participants

This is a cross-sectional mixed methods study comparing walking biomechanics of young stroke survivors to age-matched healthy able-bodied controls who were recruited from six hospital sites in Wales, UK between September 2018 to October 2018. This study was approved by the NHS Research Ethics Committee (Regional Ethics Committee 6) and Health Research Authority (UK) (REC reference: 18/WA/0265). Informed written consent to take part in this study was obtained from each participant.

Twenty-four young stroke survivors aged between 18 and 55 years were recruited and agreed to participate. Inclusion criteria: Haemorrhage or infarct stroke within the last three years that is evident from a computerised tomography (CT) or MRI scan and be able to walk continuously for at least 3 minutes. Young stroke survivors who were diagnosed with a respiratory disease, musculoskeletal disease, injury, or an auto-immune disease that was the predominant health concern or the major factor that limited their ability to walk rather than the stroke were excluded from this study.

Ten control participants of similar age and sex who had no history of stroke, neurological, musculoskeletal, cardiovascular, auto immune, or respiratory disease and were able to walk at least 3 minutes unaided were recruited. Very physically active (e.g., elite/sub-elite athletes) individuals, or participants who smoke or have smoked in the past were excluded from this study. We chose this criterion because we have reported the physiological efficiency of this group of stroke survivors and control population in other papers[10,11] as this data was captured simultaneously to the biomechanical data we present in this manuscript. As we have shown previously in these papers this control group has a similar metabolic energy expenditure to the controls during walking. This should in theory illustrate that they are an appropriate control group for comparison to this clinical population and do not represent the extremes of being highly trained or sedentary.

Outcome Measures

Demographic Data

Demographic data included age, body mass, height, time since stroke, type of stroke, whether the right or left side was predominantly affected by the stroke was used to determine the paretic and non-paretic limb, and employment status.

Measurement of walking speed

All participants walked at their self-selected speed for 3minutes up and down a 15m walkway with timing gates (Brouwer Timing Systems) situated 5m from either end of the walkway and average walking speed calculated from the last minute of walking as recommended and used in previous work[10,11]. Participants were required to turn around at each end of the walkway, but walking speed during this time was not used to compute overall walking speed. Part of the rationale behind this is to ensure that participants reach a relatively ‘steady-state’ gait and walking speed. Participants were provided with a verbal description of the data collection procedures and although no formal familiarisation process was provided as data was captured over 3 minutes of continuous walking, it is expected that participants became acclimatised by the final minute of data capture which is when the data was analysed from.

Measurement of joint kinematics, kinetics, temporal and spatial parameters

An eight-camera optoelectronic motion capture system (Miqus, Qualisys motion capture system, Qualisys, Sweden) was placed around a 15m walkway with four Kistler force plates embedded within a walkway to capture three-dimensional walking biomechanics (range of motion, joint moment and joint power) at the same time as walking speed was captured. Retro-reflective markers were placed on anatomical landmarks to define joint centres and body segments using the marker set previously described[11,36]. Motion analysis data was collected at 120Hz and ground reaction forces at 1200Hz. A static standing motion analysis trial was recorded for each participant to generate a participant-specific calculation of the location of joint centres and then participants completed seven repeat walking trials of approximately 15m in length.

Data was digitised in Qualisys Track Manager (Qualisys, Sweden) and then exported for modelling and analysis with Visual 3D (C-Motion, Rochelle, USA). A model specific to the height and body mass of each participant was created. The inertial parameters were calculated for the pelvis, hip, knee, and ankle using inverse dynamics. This allows specific constraints to be applied at the joints of the virtual model so to limit rotation and or translation. The pelvis permitted six degrees of freedom, but only sagittal, coronal, and transverse plane rotation was permitted at all other joints. Gait events (initial contact and foot off) were defined from contact with the force plates and used to calculate stride length, stride width, and for right and left limbs step length and stance time. Visual 3D was used to calculate and extract specific walking biomechanics parameters.

Statistical Analysis

Statistical analysis was conducted using SPSS Version 26. All data was checked for normality using the Shapiro-Wilko test and measures of skewness and kurtosis. Fifty walking biomechanics (joint angle, range of motion, joint moments and powers) parameters recommended or previously used[37,38] were correlated to walking speed assuming that walking speed is a key indicator of walking performance[10] using a Spearman correlation. A list of all parameters used are provided in Appendix 1. Stroke survivors were divided into slow (<0.79m/s) or fast (>0.80m/s) with mean and 95% confidence intervals (CI) calculated for the paretic/non-paretic limb of each participant within each group for each parameter that significantly correlated greater than $\rho=0.500$ to walking speed with Kruskal Wallis and post-hoc analysis using a Mann Whitney test to compare between walking speed groups. Effect sizes were calculated using Cohen d for parameters with a significant between group comparison. Values presented are group means and confidence intervals (CI), unless otherwise specified.

Results

Walking speed of stroke participants in the slow group (all data reported mean (95% confidence interval) was 0.54m/s (CI: 0.43- 0.64), fast group 1.18m/s (CI: 1.08- 1.27) and control 1.45m/s (CI: 1.39- 1.50). Demographic data can be found in Table 1. Participants in the slow group were significantly older (47.6 years, CI: 42.8- 52.4) than the fast group (39.1 years, CI: 30.68- 47.51, $p=0.001$), but the fast group were significantly younger than the control (44.2 years, CI: 36.7-51.6, $p=0.001$). Mass and height were similar across all groups ($p\geq0.170$). Time since stroke ($p=0.585$) was similar between the fast and slow groups. Even though all participants were employed pre-stroke, only n=1/15 participant in the slow group and n=3/11 participants in the fast group returned to employment post-stroke. Step length of the paretic leg of the slow group was significantly shorter (0.32m (0.24-0.40)) than the fast group (0.52m (0.32- 0.70)) p=0.024, and control (0.68m (0.63- 0.73), p≤0.001). The latter comparison had a notable effect size (d=0.73), others were d≤0.23. Step length of the non-paretic leg was also significantly shorter for the slow group compared to the fast group (p=0.004) and control (p=<0.001), effect size for the latter (d=0.47) indicates medium effect size of the difference between slow and control. Only stance time for the non-paretic leg of the slow group (71.0% (65.6-76.3) was significantly longer than the fast group (61.6 (55.4- 67.8) p=0.016) and control (61.0 (60.0- 62.0), p=<0.001 with an effect size of 0.51. Stance time of the paretic leg was similar across groups (p=0.455).

Ten walking biomechanical parameters correlated above ρ=0.500 to walking speed in young stroke survivors to determine key biomechanical parameters to be used to compare groups. For the paretic leg: range of sagittal plane motion of the pelvis (anterior and posterior tilt) (ρ = 0.550, p=0.005), range of hip adduction and abduction (ρ = 0.564, p=0.014), and peak hip abduction moment (ρ = 0.692, p<0.001) were all positive correlations indicating that as the range of motion, peak angle or moment increased, walking speed increased (Table 2). Peak hip extension angle (ρ = -0.674, p<0.001), peak hip flexion moment (ρ = -0.626, p=0.002) were all negative correlations indicating that as peak angle or moment decreased, walking speed increased, Table 2.

For the non-paretic leg: peak pelvis obliquity up (ρ = 0.647, p=0.001), and down angle (ρ = -0.663, p=<0.001) range of internal and external motion at pelvis (ρ = 0.567, p=0.004) and peak ankle plantarflexion moment (ρ = 0.657, p=0.001) were all positive correlations indicating that as range of motion, peak angle and moment increased walking speed increased, Table 3. Peak flexion moment at the hip (ρ = -0.657, p=0.001) is a negative correlation suggesting as peak moment decreased walking speed increased (Table 3).

The paretic limb of the slow group exhibited a significantly greater range of sagittal plane motion at the pelvis (anterior to posterior tilt) (4.86°, CI: 3.56- 6.16), reduced hip extension (-3.16°, CI: -9.68- 3.34), and range of abduction and adduction (10.98°, CI:8.67- 13.28) compared to the paretic leg of the fast group (10.25°, CI: 8.56- 11.93, *p*<0.009), (-15.92°,CI: 24.39- -7.44, *p*=0.022), (16.24°,CI: 1.13- 19.34, *p*=0.003), and the control (4.56°, CI: 2.96- 6.15, *p*=0.007), (-13.70°,CI: -18.06- -9.34, *p*=0.011), (13.85°, CI: 11.45- 16.25, *p*=0.087) (Figures 1, 3 and 5). Effect sizes across all parameters that were significant indicate small to medium effect (d=0.02 to 0.31). All other kinematic parameters were similar between groups (p>0.184).

For joint kinetics of the paretic limb, peak flexion moment of the hip was significantly less for the slow group (-0.51 Nm/Kg, CI: -0.86- -0.16) compared to the fast group (-0.69 Nm/Kg, CI: -0.91- -0.47, *p*=0.029) and control (-0.80 Nm/Kg, CI: -0.94- -0.66, *p*=0.006). Peak abduction moment at the hip was similar across all groups (*p*=0.659) (Figures 2, 4 and 6).

The non-paretic leg of the slow group exhibited a significantly reduced peak up angle of pelvic obliquity (-2.23°, CI: -0.39- -5.06), compared to the control (6.54°, CI: 4.71- 8.38) *p*=0.032), and less but not significant compared to the fast group (4.52° (CI: 3.19- 5.85) *p*=0.351) (Figure 3). Peak flexion moment at the hip joint for the slow group (-0.51Nm/Kg (CI: -0.86- 0.16) was significantly less than the fast group (-0.69 Nm/Kg (CI: -0.91- -0.47) p=0.040) and control (-0.80 Nm/Kg (CI: -0.94- -0.66) *p*=0.002) (Figure 2). Again, effect sizes for the parameters that were significant were small to medium across all parameters (d=0.18 to 0.42). All other parameters were not significant (*p*≥0.091).

Discussion

We are the first to report a comparison of biomechanical function during walking in young stroke survivors (less than 55years) classified by walking speed as slow (less than

0.79m/s) or fast (greater than 0.80m/s) similar to that defined by Perry et al[35]. We have identified ten key walking biomechanical parameters that are correlated to walking speed in young stroke survivors and have compared these between stroke survivors who walk slow (<0.79m/s) or fast (>0.80m/s) according to Perry et al[35]. In agreement to our hypothesis some sagittal plane kinetic and kinematic variables were correlated with walking speed, but five of the parameters were in the coronal or transverse plane. These included the range of sagittal and transverse plane motion at the pelvis, peak pelvis up and down, peak hip extension angle, range of hip adduction and abduction, peak hip flexion and abduction moment, and peak plantarflexion moment at the ankle joint. A discussion of the clinical implications of these biomechanical changes and the practical applications for rehabilitation strategies are discussed below and presented comprehensively in Tables 2 and 3.

We suggest that these kinematic and kinetic factors closely modulate walking speed post-stroke and can be considered specific musculoskeletal factors to target through an intervention/rehabilitation programme to improve the quality of walking biomechanics and increase walking speed in young stroke survivors. This may in-turn help young stroke survivors be able to more easily complete activities of daily living (e.g., such as dressing, shopping), take part in social activities, sport and recreation and return to employment[10]. All of these are routinely described as key aims of young stroke survivors[10,39-49], but difficulty walking often compromises the ability to complete them.

There are similarities between the findings from our study of younger stroke survivors and others who report walking biomechanics of older stroke survivors. However, we are the first to report how biomechanical function changes in participants grouped by walking speed post-stroke as an indicator of severity of stroke rather than viewing simply as one large heterogenous grouping. This allows for a much more detailed analysis of how those severely affected by a stroke walk and provides much needed insight into how to improve their walking performance.

This seems particularly pertinent for young stroke survivors as our previous work[10,11] and others[17] suggest that often young stroke survivors are either mildly affected by a stroke (and therefore would be classified as the fast group in this paper) or severely affected (and be classified as the slow group) with few participants moderately affected. Platts et al[17] suggests this is because young stroke survivors are more likely to be able to recover well from a less severe stroke compared to older stroke survivors, while if they experience a more severe stroke they may be able to survive the stroke because they are younger (albeit their gait is severely affected), whereas it is more likely to be fatal in an older adult. Therefore, rehabilitation needs to be adapted to accommodate for the variation in function, and that a generic model is not fit for purpose but basing it on walking speed may provide key inferences to support intervention design.

In the following paragraphs we provide detailed explanations on the clinical implications of the observed biomechanical changes with stroke affecting walking speed. The practical applications for rehabilitation strategies are also discussed below. A systematic and comprehensive description of clinical implications and rehabilitation intervention are presented in Tables 2 and 3.

The reduced range of pelvis coronal plane of the non-paretic leg by the slow group is indicative of reduced ability and reluctance to transfer load onto the paretic limb at the beginning of the gait cycle[6,50,51]. As load is transferred onto the other leg (i.e., the paretic leg) the characteristic up movement of the contralateral side pelvis via the non-paretic leg is less due to instability and inability to bear load through the paretic limb. This is often due to reduced quadriceps strength and loss of proprioception between the foot and the floor meaning the hip joint is unable to flex at this early point of the gait cycle[6,25,51]. This will also reduce the range of flexion at the knee joint, hip abduction and coronal plane movement of the pelvis during loading response which will reduce step length as we report. However, effect sizes across these parameters are comparatively small, suggesting that whilst there is a difference between groups for the individual parameters, they are not the sole cause of why some stroke survivors walk slower but likely instead an accumulation of multiple contributary biomechanical factors.

Reduced ability to transfer and accept weight on one limb at an early stage in the gait cycle is likely to be the detrimental cause of the reduced function of the paretic limb (and compensation by the non-paretic limb) throughout the rest of the gait cycle causing impaired single limb support and limited progression forwards which will slow walking speed and also, as we report in this study and others[10,52-54], reduce step length and increase stance time. Progression forwards in the direction of travel is also compromised by spasticity in the hip flexor muscles of the paretic limb (and non-paretic limb) restricting the range of hip extension as we report during mid-stance and terminal stance[25,55-57]. In the slow group, peak hip extension angle of the paretic leg was a mean difference of 12.76° less than the fast group and 17.01° less than the control. This reduced range of motion is often caused by increased sedentary behaviour and counteraction from weakness in the trunk musculature following a stroke[25,58]. Therefore, rehabilitation post-stroke should focus on increasing range of motion and flexibility of hip flexors and strengthen trunk musculature[9,14,59,60].

Reduced peak angle of ankle joint plantarflexion is a hallmark of stroke survivor gait[3-5,11,23]. Muscle weakness and/or spasticity of the calf musculature reduces the power generating capacity of the ankle joint complex limiting push off capabilities to aid propulsion and movement in the direction of travel[22,61,62] which can also reduce step length and increase stance time. However, in this study only peak plantarflexion moment of the ankle joint on the non-paretic leg significantly correlated to walking speed, but the peak moment was similar between slow, fast and control groups suggesting the function of the ankle joint may not be the key determinant in stroke survivor gait, although undoubtedly it remains an important factor. Other factors that we do report such as reduced range of hip extension, reduced hip flexion moment and knee hyperextension can all contribute to reducing the plantarflexion angle and moment at the ankle joint which can equally have a detrimental effect on biomechanical function during walking[63]. This suggests that rehabilitation and gait retraining should focus on improving function throughout all phases of the gait cycle rather than just propulsion with the function of the pelvis and hip at the centre of this with focus on the facilitation of weight acceptance during the early loading response phase of the gait cycle.

The fast stroke group's biomechanical function was similar to the control across all parameters. The average walking speed for the fast group (1.18m/s) is less than the control (1.45m/s), but it is significantly faster than the 0.80m/s cut-off defined by Perry et al[35]for walking outdoors. This suggests stroke survivors in the fast group were highly functional which is also likely why 30% of participants in that group returned to employment and only 7% in the slow group were able to[2]. This highlights the importance of promoting physical function and walking performance post-stroke to facilitate return to employment of young stroke survivors is[10], but as yet is largely neglected in favour of focusing on vocational interventions[64].

The limitations of this study are that this may be considered a relatively small sample of participants for certain types of medical studies and there is some inter-participant variation across all groups with some overlapping of values between groups. However, when compared against sample sizes of other gait studies reporting similar data from clinical populations, this remains one of the largest sample sizes in stroke studies on gait. We correlated fifty biomechanical parameters to walking speed to deduce appropriate parameters that influence walking speed and therefore are confident that the p value is representative of differences between groups.

The slow group were significantly older (by ~8 years) than the fast group which may be a possible reason for why those participants walk slower and have significant gait anomalies. However, the mean age of the slow group participants is still less than 50 years indicating there is limited age-related decline in function and instead gait changes are dependent on the stroke. The fast group were faster than the 0.80m/s cut off speed with the slowest walking speed by two participants at 1.0m/s, but the fast group were slower than the control indicating some residual musculoskeletal and neuromuscular changes post-stroke. This is also similar cut-off walking speed that we proposed could predict the ability to return to employment after a stroke (0.93m/s)[10].

We did not record or can take into account the duration, type of, or adherence to rehabilitation that participants may have been administered before taking part in this study as this is a cross-sectional study, but future studies could use the work from this manuscript as a basis for measuring changes in gait performance in response to a rehabilitation programme. The variation in walking speed, and potential to return to employment post-stroke is underpinned by a multitude of factors (cognition, stroke severity, confidence, function of upper arms and more), not just walking biomechanics which we cannot account for in this study. Future work should aim to account for these changes and test how they may/may not affect walking performance and biomechanical function which may also help to inform rehabilitation guidelines.

This study has identified ten key walking biomechanics parameters that are strongly related to walking speed in young stroke survivors and can be used to focus an intervention/ rehabilitation programme(s) to improve the quality of walking biomechanics which may in turn help to increase walking speed, function, and ability to complete activities of daily living and improve quality of life of young stroke survivors.

Acknowledgements

Thank you very much to Claire Butterworth, Karl Jackson, Louisa Walker, Nia Rees, Renee Groenevelt and Abigail Clayton for their assistance with recruitment of participants and data collection.

Conflict of interest

The authors declare that there is no conflict of interest or competing interests

Funding

Stroke Research Innovation Education Fund

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