Biomechanical correlates for recovering walking speed following a stroke. The potential of tibia to vertical angle as a therapy target

Kerr[1], Rowe[1], Clarke[2], Chandler[2], Smith[3], Ugbolue[4], Pomeroy[2]

[1]Biomedical Engineering Dept. University of Strathclyde, Glasgow, UK
[2]School of Health Sciences, University of East Anglia, Norwich, UK
[3]English Institute of Sport, Sheffield, UK
[4]School of Science and Sport, University of West of Scotland, Hamilton, UK

Corresponding author
Dr Andy Kerr
Email: a.kerr@strath.ac.uk
Tel: 0141 548 2855
Dept of Biomedical Engineering
University of Strathclyde
50 George St
Glasgow
G1 1QE

Abstract

Background

Recovering independent walking is a priority for stroke survivors. Community walking requires speeds exceeding the average values typically achieved at discharge (0.7 m/s). To improve outcomes there is a need to clarify the factors associated with recovery of functional walking speeds.

Research question

Which biomechanical variables correlate significantly with improved walking speed following rehabilitation in acute stroke patients.

Methods

The study was embedded in a larger clinical trial testing efficacy of a gait training splint. Participants, within 6 weeks of their stroke and exhibiting abnormal gait, were recruited. Using a valid and reliable video-based system, specific kinematic measures were recorded before randomisation (baseline), after a 6-week rehabilitation phase (outcome) and six months after stroke (follow-up). Measures of temporospatial symmetry, knee angular velocity and tibia to vertical angle were added to clinical measures and correlated with change in speed.

Results

23 participants were recruited, (mean age 67.7±16.7 years, 19.2±9.0 days after stroke and 73.9% male), with 20/23 assessed at outcome and 17/23 at follow-up. Drop out was due to withdrawal (3) and technical failure (3). Walking speed increased by 0.15±0.21 m/s (outcome), and 0.21±0.14 m/s (follow-up) from baseline (0.50±0.20 m/s). This increase correlated with an increase in step length (r=0.88) and change in angle of tibia at initial contact (r=-0.59), foot flat (r=-0.61) and terminal contact (r=0.54).

Significance

This study of gait recovery among acute stroke patients demonstrated modest improvements in walking speed. Walking speed by follow-up (0.71 m/s) classified the group as community walkers (>0.66 m/s) but still too slow to safely use a pedestrian road crossing. Change in step length and tibia to vertical angle significantly correlated with increased walking speed. This finding provides distinctive targets for therapy aimed at improving community walking among stroke survivors. This hypothesis should be tested prospectively in future studies.

Introduction

A key rehabilitation focus for stroke survivors is the recovery of walking [1]. While current rehabilitation approaches certainly enhance recovery [2], by discharge outcomes remain disappointing with average speeds around 0.7 m/s [3]. This speed is well below age-matched healthy peers (1.21 to 1.32 m/s) [4] and too slow to safely use a pedestrian road crossing in the United Kingdom (1.2 m/s) [5]. A slow gait is not just a barrier to outdoor mobility, and potentially physical activity participation, it is also a predictor of future disability, health and care needs and has been associated with falls and reduced survival [6]. There is an urgent need for better outcomes from rehabilitation if a return to functional walking is to be considered an achievable goal for the majority of stroke survivors.

Rehabilitation outcomes may be improved by targetting therapy at those impairments most associated with recovery [7]. Biomechanical analysis of movement has long provided precise characterisation of the underlying substrates of walking impairment in children with cerebral palsy, helping to guide surgical [8] and/or orthotic intervention [9]. Recently we demonstrated the value of this approach through identifying the variables associated with recovery of the sit-to-stand movement in stroke patients during the early stages of their rehabilitation [10]. Studies of gait among chronic stroke survivors have established clear relationships between biomechanical variables and gait function with the promise of differentiating between true motor recovery (i.e. recovery of the pre-stroke gait pattern) and compensation [11, 12]. Impaired forward propulsion on the paretic side (a reported consequence of plantarflexion weakness and poor positioning of the trailing leg during late stance) directly impacts on gait speed [12-14] leading to the development of compensatory mechanisms such as an increased contribution to forward propulsion from the paretic side hip (so called ‘pull-up’ compared to the more usual “push-off”). Such compensations may preserve limited function but produces a slow, fatiguing, gait and arguably constrains an individual’s recovery of gait speeds that are compatible with community mobility [15]. There is, therefore, a need to quantify the biomechanical variables associated with recovery of gait speed, particularly in individuals early after stroke, to improve rehabilitation interventions aimed at recovering community mobility.

Biomechanical gait analysis can be achieved in clinical environments using video-based movement analysis systems [16], such as the one used in this study [17], in which video film is replayed at slow speed or using freeze frame facilities. The convenient nature of these systems enable observations of gait early after stroke and they have been validated for use with stroke populations [17]. Valid, reliable measures of the biomechanical substrates of walking ability and performance can be made in people early after stroke [18, 19]. Indeed, changes in brain activation, as measured by near-infra-red spectroscopy, have been significantly correlated with improvements in biomechanical measures of walking [20] giving further validation to this approach.

We hypothesise that a biomechanical analysis of gait before and after rehabilitation, in a cohort of individuals early after stroke, will reveal the biomechanical variables statistically significantly correlated with a change in walking speed, thereby providing targets for therapy aimed at optimising gait function.

Methods

This was a prospective correlational study embedded in an observer-blind, randomised, controlled, clinical trial [21]. Measures were taken before randomisation (baseline), immediately following a 6-week rehabilitation phase (outcome) and six months after stroke (follow-up). The clinical efficacy finding was that a custom-made, therapist-fitted, SWIFT Cast (providing optimal alignment of the lower limb to the ground during walking) did not provide additional benefit compared to conventional physical therapy (CPT) at either outcome or follow-up, consequently the groups were merged for the purposes of this study.

Ethical and Research Governance approvals were in place before screening for participants began (National Research Ethics Service reference 09/H0310/87). All participants provided informed consent. The trial was registered on the Controlled Clinical Trials database (ISRCTN 39201286).

Participants were prospectively screened from consecutive admissions to two stroke services. Those who met the study criteria were provided with information about the trial and invited to consider participation. The inclusion criteria were: adults over 18 years old; 3 to 42 days post ictus; able to walk at least 3 metres without either human or device assistance, abnormal initial floor contact and/or impaired ability to take full body weight through the paretic limb; no lower limb contractures or loss of skin integrity; and ability to follow one-stage instructions.

Outcome measures

Gait parameters were measured from each participant as they walked at a self-selected pace along a 6m walking-mat placed in either a University movement laboratory or hospital location of sufficient dimension and free of hazards. Circular, black and white paper markers (diameter 4.5 cm) were attached to participant's skin or close fitting clothing overlying the hip, knee and ankle joint centres, when viewed in the sagittal plane, and on the heel and toe of each leg. These markers helped identify key anatomical landmarks for subsequent video processing and calculation of gait parameters. The walking-mat was marked with evenly spaced lines 1cm, 5cm and 10cm apart.

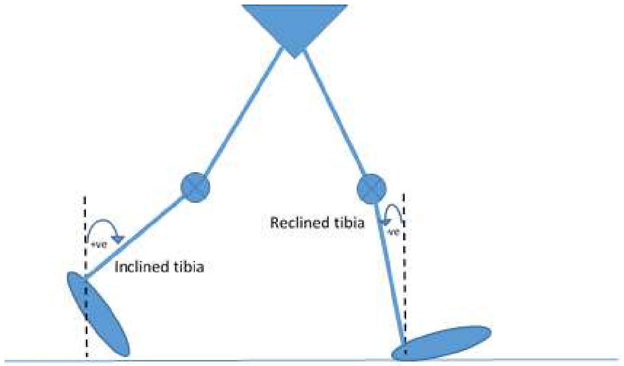
A high-speed (210fps) digital video camera (EXFH20, Casio, Tokyo, Japan) located perpendicular to, and approximately 3m away, from the walking-mat captured a minimum of 4 m of the central part of the walk. Infrared light beams were placed at both ends of the mat (i.e. at 0 m and at 6 m), see figure 1. The infrared light beams were connected to a light source placed in view of the camera. When either beam was broken, the light source was activated and captured by the camera. In this way participants' walking speed could be calculated over the entire 6 m walking-mat. This setup was adjusted for participants who could only walk for 3 m independently by placing the infrared light beams at 1.5 m and 4.5 m. Concurrent validity of this system has been tested against a motion analysis system (Vicon, Oxford Metrics, UK) with mean differences ranging from -0.9 to 0.8 degrees. The test-retest (intra-rater) reliability is also good with ICC values for stroke survivors ranging between 0.97 (tibia to vertical angle at initial contact) and 1.00 (step time). Further details available from Ugbolue et al. [17].

Using this technique, a range of biomechanical parameters were available for analysis. Speed [22], step length [23] and inter limb step symmetry [24] were selected for their known relationship with the recovery of gait function following stroke. Acknowledging that a change in these variables could result solely from compensatory mechanisms it was important to include variables with the potential to reflect motor recovery, particularly if we hoped to inform early rehabilitation practice, therefore knee angular velocity [25] and the tibia to vertical angle were included [12]; the full list of extracted variables is detailed below:

1. Gait speed (m/s)
2. Step length.
3. Peak knee angular velocity during stance (PKAV, degrees/s).
4. Ratio of step times (RST) between the paretic (P) and non-paretic (NP) sides.
5. Ratio of step lengths (RSL) between the P and NP sides.
6. Tibia angle (TA, degrees) with respect to the vertical (see figure) at the following gait events:
    a. initial contact (TAIC)
    b. foot flat (TAFF)
    c. mid-stance (TAMS)
    d. heel rise (TAHR)
    e. terminal contact (TATC)
    f. mid-swing (TASW)

As widely used standard measures of mobility the Functional Ambulatory Category (FAC) [26] and Modified Rivermead Mobility Index (MRMI) [27] were recorded by the research team immediately before each gait capture session.

Calculation of tibia to vertical angle



Data processing
Each video was processed by an assessor, not involved in the data collection, using Sports Motion video analysis software - Pro-trainer 10.1 (Sports Motion Inc. CA, USA) according to a standard operational procedure produced for the trial. The data were extracted by observing the video-film and using the software analysis tools. The video-film was played back in slow motion and timed using the software analysis tools to determine step times. It was also viewed frame-by-frame to determine step lengths using the spatial location of the feet on the grid [17]. The peak angular velocity of the knee during stance was recorded from the point in the gait cycle when the participant was perpendicular to the camera. Finally, the tibia to vertical angle was determined by using the freeze frame mode and the computer-generated goniometer, see figure for illustration.

A second, blind, assessor then duplicated this process to identify potential errors. Where a discrepancy was detected in either processing or entry in the database these were investigated and resolved. Discrepancies between assessors that could not be resolved resulted in this data being excluded from the analysis and a technical failure recorded instead.

Statistical analysis
Correlations (Pearson's correlation coefficient) between change in walking speed and change in the gait parameters were conducted. Change in the individual gait parameters across the time points (baseline, outcome and follow-up) were tested for statistical difference with one-sample t-tests. The significance level for the t-tests was reduced to 0.025, using a bonferroni correction, to temper the possibility of a type 1 statistical error.

Results

The baseline characteristics, including gait parameters, of the 23 participants are summarised in table 1. The participants had a mean age of 67.7 (SD 16.7) years, were a mean of 19.2 (SD 9.0) days after their stroke and 17/23 (73.9%) were male. Most (20/23, 87%) participants had an infarct stroke, with 2/23 (8.7%) having a haemorrhagic stroke, this clinical information was missing for one participant. The primary motor cortex was involved in 10/23 (43.5%) participants and 11/23 (47.8%) had their right side affected. At baseline the mean walking speed was 0.5 (SD 0.2) m/s and the mean Modified Rivermead Mobility Index (MRMI) was 32.5 (SD 5.5). Of the 23 participants measured at baseline, 20 remained in the trial at outcome and 17 at follow-up. Reasons for attrition were withdrawal of consent (n=3) and measurement technical failure (n=3).

Table 1: Baseline characteristics of participants (n=23)

	Mean (SD) or N (%)
Male	17 (73.9)
Type of stroke	
▪ Haemorrhage	2 (8.7)
▪ Infarct	20 (87.0)
▪ Unknown	1 (4.4)
Right paretic side	11 (47.8)
Motor cortex	10 (43.5)
*FAC	3.2 (1.0, 2.5)
Age (years)	67.6 (16.7)
Days since stroke	19.2 (9.0)
MRMI	32.5 (5.5)
Walking speed (m/s)	0.5 (0.2)
P Step length (cm)	34.8 (11.4)
NP Step length (cm)	36.7 (10.9)
NP peak knee velocity (deg/s)	22.9 (4.8)
P Peak knee velocity (deg/s)	18.7 (5.8)
Tibia to vertical angle P/NP	
▪ Initial contact (TAIC)	-1.2 (8.6)/ -1.8 (7.7)
▪ Foot flat (TAFF)	3.7 (6.1)/ 2.4 (4.5)
▪ Mid stance (TAMSt)	10.6 (4.5)/10.35 (3.2)
▪ Heel rise (TAHR)	28.6 (4.1)/31.02 (3.8)
▪ Terminal contact (TATC)	40.7 (5.2)/43.7 (5.3))
▪ Mid swing (TAMSw)	27.0 (6.0)/30.27 (5.6)
Ratio of stance times	0.0 (0.1)
Ratio of step lengths	0.0 (0.1)

*Median and IQR

Change in walking speed and gait parameters

Table 2 details the change in walking speed and biomechanical parameters from baseline, at outcome and follow-up. This shows significant change in walking speed at outcome (mean change 0.15 m/s, p=0.004) and follow-up (mean change 0.21 m/s, p=0.002). Step length increased on both the paretic (P) (10.18 cm+/- 8.31, p=0.001) and non-paretic (NP) (7.52 cm +/- 8.31, p=0.001) sides by outcome with further increases at follow-up on the P (14.15 cm+/- 14.88, p=0.002) and NP (13.77 cm +/- 11.14, p<0.000) sides. There were also statistically significant changes in the tibia to vertical angles at the following gait events by follow-up:

- Initial contact: Mean reductions of 8.86 (P) and 10.59 (NP) degrees, p<0.001. Indicating the tibia became more reclined with respect to the vertical.

- Foot flat: Mean reductions of 5.84 (P) and 5.87 (NP) degrees, p<0.001. Indicating the tibia became more reclined with respect to the vertical.

- Terminal contact: A mean increase of 4.10 (P) degrees, p=0.007. Indicating the tibia became more inclined with respect to the vertical.

Table 2: Change in gait parameters from baseline; at outcome (n=20) and follow-up (n=17). The mean (SD) are given when the variable is normally distributed and the median (IQR) when not. No 95% CI is provided when the outcome is not normally distributed. NP = non paretic side, P = paretic side

	Outcome			Follow-up		
	Mean (SD)/ Median (IQR)	95% CI	p-value	Mean (SD)/ Median (IQR)	95% CI	p-value
Walking speed (m/s)	0.15 (0.21)	(0.05,0.25)	**0.004**	0.21 (0.14,0.31)		**0.002**
NP step length (cm)	7.52 (8.31)	(3.88, 11.16)	**0.001**	13.77 (11.14)	(8.31, 19.23)	**<0.000**
P step length (cm)	10.18 (11.07)	(5.32, 15.03)	**0.001**	14.15 (14.88)	(6.86, 21.44)	**0.002**
NP peak knee velocity (deg/s)	3.51 (-1.71,12.16)		0.067	4.11 (1.72,5.63)		0.08
P peak knee velocity (deg/s)	4.17 (-4.72,8.94)		0.101	6.65 (-3.56,9.67)		**0.044**
Tibia to vertical angles (P/NP)						
Initial contact (TAIC)	-6.97 (8.58) -10.80 (9.30)	(-10.99,-2.96) (-14.84 -6.69)	**0.002** **0.000**	-8.86 (7.95) -10.59 (8.46)	(-13.09,-4.62) (-14.74,-6.45)	**<0.001** **<0.001**
Foot flat (TAFF)	-5.02 (6.49) -6.10 (5.80)	(-8.06,-1.98) (-8.94,-3.25)	**0.003** **0.000**	-5.84 (5.11) -5.87 (4.02)	(-8.56,-3.11) (-7.84,-3.90)	**<0.001** **<0.001**
Mid-stance (TAMS)	-0.34 (4.77) -2.85 (5.31)	(-2.57,1.90) (-5.18 -0.52)	0.755 **0.027**	-1.92 (4.83) -2.21 (4.77)	(-4.49,0.66) (-4.55,0.13)	0.134 0.084
Heel rise (TAHR)	0.05 (3.81) -2.33 (5.14)	(-1.73,1.83) (-4.58,-0.07)	0.954 0.057	0.01 (5.68) -1.17 (6.29)	(-3.02,3.03) (-4.25,1.91)	0.997 0.468
Terminal contact (TATC)	3.05 (5.05) 0.78 (4.60)	(0.69,5.41) (-1.24,2.79)	**0.014** 0.460	4.10 (5.24) 3.68 (6.61)	(1.31,6.90) (0.44,6.92)	**0.007** **0.042**
Mid-swing (TASW)	-2.49 (7.51) -5.03 (9.35)	(-6.0,1.03) (-9.12,-0.93)	0.155 **0.027**	-1.82 (7.80) -1.42 (8.67)	(-5.98,2.33) (-5.66,2.83)	0.365 0.523
Ratio stance time (RST)	0.02 (0.08)	(-0.01,0.06)	0.205	0.01 (0.04)	(-0.02,0.03)	0.473
Ratio step length (RSL)	0.04 (0.11)	(-0.01,0.09)	0.130	0.08 (0.1)	(0.02,0.13)	**0.007**

Table 3 details the correlations between change in walking speed and change in the biomechanical gait parameters. At outcome there was a strong, statistically significant, correlation with step length on both the paretic (P) (r=0.88, p<0.000) and non-paretic (NP) (r=0.87, p<0.000) sides. The tibia to vertical angle at foot flat (NP) and terminal contact (P and NP) correlated moderately with the change in walking speed (r values ranged between 0.48 and 0.52). By follow-up the increase in walking speed continued to be strongly correlated with step length on both P (r=0.85, p<0.000) and NP (r=0.85, p<0.000) sides. Moderate negative correlations were recorded for the tibia to vertical angle at initial contact on the P(r=-0.59, p=0.017) and NP (r=-0.53, p=0.034) sides indicating speed improvement was associated with a more reclined tibial angle during early stance. This relationship persisted at foot flat on the P (r=-0.61, p=0.012) but not the NP side (r=-0.08, p=0.77). Positive correlations at terminal contact on both the P(r=0.53, p=0.036) and NP sides r=0.54, p=0.032) indicate walking speed improvement was associated with a more inclined tibial angle during the terminal stages of stance.

Table 3: Correlation between change in walking speed and change in biomechanical parameters

	Outcome (n=20)		Follow-up (n=16)	
	Correlation (95% CI)	p-value	Correlation (95% CI)	p-value
NP Peak knee velocity	-0.08 (-0.51,0.37)	0.730	0.17 (-0.34,0.60)	0.515
P Peak knee velocity	-0.08 (-0.50,0.38)	0.755	0.31 (-0.20,0.69)	0.230
NP Step length	0.87 (0.69,0.95)	**0.000**	0.85 (0.61,0.95)	**0.000**
P Step length	0.88 (0.72,0.95)	**0.000**	0.85 (0.61,0.95)	**0.000**
Tibial angle (P/NP):				
Initial contact (TAIC)	-0.28 (-0.65,0.18) -0.41(-0.72, 0.04)	0.227 0.075	**-0.59** (-0.84,-0.13) **-0.53** (-0.81,-0.05)	**0.017** **0.034**
Foot flat (TAFF)	-0.10 (-0.52,0.36) -0.49(-0.77,-0.06)	0.677 **0.029**	**-0.61** (-0.85,-0.17) -0.08 (-0.56,0.43)	**0.012** 0.770
Mid-stance (TAMS)	-0.01 (-0.45,0.44) -0.43 (-0.73,0.02)	0.973 0.061	-0.04 (-0.53,0.46) -0.05 (-0.53,0.46)	0.880 0.847
Heel rise (TAHR)	0.20 (-0.27,0.59) 0.01 (-0.43,0.45)	0.399 0.967	0.29 (-0.24,0.69) 0.31 (-0.21,0.70)	0.271 0.235
Terminal contact (TATC)	0.48 (0.05,0.76) 0.52 (0.10,0.78)	**0.032** **0.020**	**0.53** (0.04,0.81) **0.54** (0.06, 0.82)	**0.036** **0.032**
Mid-swing (TASW)	0.08 (-0.38,0.50) 0.32 (-0.14,0.67)	0.740 0.170	-0.06 (-0.54,0.45) 0.06 (-0.45, 0.54)	0.816 0.815
Ratio stance time (RST)	-0.09 (-0.51,0.37)	0.826	0.28 (-0.25,0.68)	0.300
Ratio step length (RSL)	0.39 (-0.06,0.71)	0.710	0.42 (-0.09,0.76)	0.102
Ratio peak knee velocity	0.05 (-0.40,0.48)	0.090	0.39 (-0.14,0.74)	0.140

Discussion

This study of gait recovery among participants with altered walking ability early after a stroke (n=23), found an improvement in speed immediately after a 6-week rehabilitation phase (0.15 m/s+/- 0.21) which improved further 6 months after stroke (0.21 m/s, 0.14-0.31). Over the same time period a set of pre-selected biomechanical variables changed by a statistically significantly magnitude; specifically step length, on both paretic (14.15 cm+/-14.88) and non-paretic (13.77 cm+/-11.14) sides and the tibia to vertical angle at key points during stance phase i.e. initial contact, foot flat and terminal contact (p values ranging between <0.001 and 0.007). Clear relationships between change in speed and these biomechanical measures were evident 6 months post stroke. Step length had the strongest correlation with a coefficient of 0.85 on both paretic and non-paretic sides; moderate, though statistically significant, correlations were also present for the tibia to vertical angle at initial contact (r=-0,59(P), r=-0.53(NP)), foot flat (r=-0.61 (P)) and terminal stance (r=0.53 (P), r=0.54(NP)).

Six months after stroke the observed increase in walking speed was not only statistically significant (p=0.002) but had exceeded the minimal clinically important difference (0.2 m/s) recommended for a range of neurological conditions, including stroke [4]. This improvement compares well to other studies of gait rehabilitation [28] but has, nevertheless, resulted in a walking speed by discharge that is close to previous reports, e.g. 0.71 m/s [3, 24] and arguably still below the threshold needed for community walking, an activity considered essential, or at least very important, by 75% of stroke survivors [29]. Any interpretation of walking speed recovery needs to be considered in the context of the speeds necessary for community walking. Categories derived by Perry et al. [30] suggest our sample changed from 'limited community walker' (threshold=0.5 m/s) to 'community walker' (threshold = 0.66 m/s) but were still some way from reaching 'full community walker' (threshold = 1.16 m/s) category. Critically, the sample did not, on average, achieve the speed necessary to safely cross the road using pedestrian lights in the United Kingdom (1.2 m/s)[5].

As gait speed changed so did the tibia to vertical angle, becoming progressively more reclined at initial contact and inclined at terminal stance. Developing a more normal angulation of the tibia with respect to the vertical is in accordance with the pendular theory of gait [31] and consistent with the observed increase in step length. The participants therefore recovered a more normal progression of their tibia during early and terminal stance.

The observed increase in step length, which was strongly correlated with an increase in gait speed, could, conceivably, have been realised through compensatory mechanisms from the non-paretic limb and paretic hip [32]. On the other hand a change in the inclination angle of the tibia during the load acceptance and propulsive phases of gait suggests a degree of recovery of the pre-morbid gait pattern. The posture of the trailing leg during terminal stance has been strongly linked with propulsion with a more reclined angle creating a better position, biomechanically, for generating the propulsive forces from the ankle plantarflexors [32]. The inclination of the tibia, in particular, is likely to represent the largest proportion of the trailing leg angle during the terminal stages of stance since hip extension is minimal, particularly among slow walking stroke survivors[32].

Changing the tibia to vertical angle to enable an increase in speed depends on the participant developing the ability to control movement about the hip, knee and ankle joints. The common practice of prescribing an ankle-foot orthosis to stroke patients to stabilise the paretic lower limb through limiting and controlling ankle movement [33] may, unintentionally, interfere with recovery of these desirable tibia to vertical angles, potentially limiting walking speed recovery without the use of compensatory mechanisms. The data in this study were collected without ankle foot orthotics so this possibility cannot be tested but should be explored in future studies with full consideration to AFO design and the characteristics of stroke participants.

Data to support targeting the tibia to vertical angle for improving walking speed in stroke patients is only useful if this variable is accessible during routine clinical practice. While step length and walking speed are easily measured, the changing angles of a lower limb segment during gait would be considered beyond the skills of visual observation or simple measurement techniques. Direct measurement of this variable is now entirely feasible through existing, low-cost technology [34] and may provide therapists (and indeed patients) with a tangible focus for gait rehabilitation, for example, by increasing attention on this angle through visual feedback. The possibility that such an approach could advance gait recovery early after stroke should be tested in future clinical trials.

The main limitation of the study was the inability to quantify individuals who could not walk without assistance. Consequently, the sample size was smaller than expected and may not reflect the general stroke population. The small sample limited the statistical analysis, future studies with larger samples, might consider clarifying the relationship between step length and tibial angle in the recovery of gait speed. Finally, the use of a single camera system, while providing a practical means of measuring gait in the hospital environment, limited our analysis to a single plane. A three-dimensional system may have revealed additional variables to explain the change in gait speed.

Conclusions

This study found that the biomechanical correlates of clinically important improvements in walking speed following rehabilitation in a group of participants early after their stroke were change in step length, tibia to vertical angle at initial contact, foot flat and terminal contact. These biomechanical variables can provide therapists with evidence based targets for their interventions.

Acknowledgements

This study was funded by the Medical Research Council (MRC) and managed by the National Institute for Health Research (NIHR). The views and opinions expressed in this paper are those of the authors and do not necessarily reflect those of the MRC, NHS, NIHR, or the Department of Health. We are also grateful for the assistance and support provided by clinicians working in the clinical centers for this trial (Norfolk and Lanarkshire) and staff in the clinical trials units in Norwich and Glasgow.

References

1. Langhorne, P., F. Coupar, and A. Pollock, *Motor recovery after stroke: a systematic review.* The Lancet Neurology, 2009. **8**(8): p. 741-754.
2. Pollock, A., et al., *Physical rehabilitation approaches for the recovery of function and mobility following stroke.* Cochrane Database of Systematic Reviews, 2014(4).
3. Taylor-Piliae, R.E., et al., *Predictors of gait velocity among community-dwelling stroke survivors.* Gait & posture, 2012. **35**(3): p. 395-399.
4. Bohannon, R.W. and A. Williams Andrews, *Normal walking speed: a descriptive meta-analysis.* Physiotherapy, 2011. **97**(3): p. 182-189.
5. Asher, L., et al., *Most older pedestrians are unable to cross the road in time: a cross-sectional study.* Age and Ageing, 2012. **41**(5): p. 690-694.
6. Studenski, S., et al., *Gait speed and survival in older adults.* Jama, 2011. **305**(1): p. 50-58.
7. Langhorne, P., J. Bernhardt, and G. Kwakkel, *Stroke rehabilitation.* The Lancet, 2011. **377**(9778): p. 1693-1702.
8. Gage, J.R., *Gait analysis. An essential tool in the treatment of cerebral palsy.* Clinical orthopaedics and related research, 1993(288): p. 126-134.
9. Morris, C., *Orthotic management of children with cerebral palsy.* JPO: Journal of Prosthetics and Orthotics, 2002. **14**(4): p. 150-158.
10. Kerr, A., A. Clark, and V.M. Pomeroy, *Neuromechanical differences between successful and failed sit-to-stand movements and response to rehabilitation early after stroke.* Neurorehabilitation and neural repair, 2019: p. 1545968319846119.

11. Bowden, M.G., et al., *Locomotor rehabilitation of individuals with chronic stroke: difference between responders and nonresponders.* Archives of physical medicine and rehabilitation, 2013. **94**(5): p. 856-862.
12. Awad, L.N., et al., *Paretic propulsion and trailing limb angle are key determinants of long-distance walking function after stroke.* Neurorehabilitation and neural repair, 2015. **29**(6): p. 499-508.
13. Peterson, C.L., et al., *Pre-swing deficits in forward propulsion, swing initiation and power generation by individual muscles during hemiparetic walking.* Journal of biomechanics, 2010. **43**(12): p. 2348-2355.
14. Hsiao, H., et al., *The relative contribution of ankle moment and trailing limb angle to propulsive force during gait.* Human movement science, 2015. **39**: p. 212-221.
15. van de Port, I.G., G. Kwakkel, and E. Lindeman, *Community ambulation in patients with chronic stroke: how is it related to gait speed?* Journal of Rehabilitation Medicine, 2008. **40**(1): p. 23-27.
16. Dunlevy, C., M. Cooney, and J. Gormely, *Procedural considerations for photographic-based joint angle measurements.* Physiotherapy Research International, 2005. **10**(4): p. 190-200.
17. Ugbolue, U.C., et al., *The evaluation of an inexpensive, 2D, video based gait assessment system for clinical use.* Gait & Posture, 2013. **38**(3): p. 483–489.
18. Pomeroy, V., et al., *A hypothesis: self-propulsion in a wheelchair early after stroke might not be harmful.* Clinical rehabilitation, 2003. **17**(2): p. 174-180.
19. Tessem, S., N. Hagstrøm, and B. Fallang, *Weight distribution in standing and sitting positions, and weight transfer during reaching tasks, in seated stroke subjects and healthy subjects.* Physiotherapy Research International, 2007. **12**(2): p. 82-94.
20. Miyai, I., et al., *Effect of body weight support on cortical activation during gait in patients with stroke.* Experimental brain research, 2006. **169**(1): p. 85-91.
21. Pomeroy, V.M., et al., *A Randomized Controlled Evaluation of the Efficacy of an Ankle-Foot Cast on Walking Recovery Early After Stroke.* Neurorehabilitation and Neural Repair, 2016. **30**(1): p. 40-48.
22. Fulk, G.D., et al., *Estimating clinically important change in gait speed in people with stroke undergoing outpatient rehabilitation.* Journal of Neurologic Physical Therapy, 2011. **35**(2): p. 82-89.
23. Chen, G., et al., *Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds.* Gait & posture, 2005. **22**(1): p. 51-56.
24. Patterson, K.K., et al., *Changes in gait symmetry and velocity after stroke: a cross-sectional study from weeks to years after stroke.* Neurorehabilitation and Neural Repair, 2010. **24**(9): p. 783-790.
25. Richards, J.D., et al., *A comparison of knee kinematic characteristics of stroke patients and age-matched healthy volunteers.* Clinical Rehabilitation, 2003. **17**(5): p. 565-571.
26. Mehrholz, J., et al., *Predictive validity and responsiveness of the functional ambulation category in hemiparetic patients after stroke.* Archives of physical medicine and rehabilitation, 2007. **88**(10): p. 1314-1319.
27. Lennon, S. and L. Johnson, *The modified rivermead mobility index: validity and reliability.* Disability and rehabilitation, 2000. **22**(18): p. 833-839.
28. Dickstein, R., *Rehabilitation of Gait Speed After Stroke: A Critical Review of Intervention Approaches.* Neurorehabilitation and Neural Repair, 2008. **22**(6): p. 649-660.
29. Lord, S.E., et al., *Community ambulation after stroke: how important and obtainable is it and what measures appear predictive?* Archives of physical medicine and rehabilitation, 2004. **85**(2): p. 234-239.
30. Perry, J., et al., *Classification of Walking Handicap in the Stroke Population.* Stroke, 1995. **26**(6): p. 982-989.

31. Kuo, A.D., *The six determinants of gait and the inverted pendulum analogy: A dynamic walking perspective.* Human movement science, 2007. **26**(4): p. 617-656.
32. Roelker, S.A., et al., *Paretic propulsion as a measure of walking performance and functional motor recovery post-stroke: a review.* Gait & posture, 2018.
33. Mulroy, S.J., et al., *Effect of AFO design on walking after stroke: impact of ankle plantar flexion contracture.* Prosthetics and orthotics international, 2010. **34**(3): p. 277-292.
34. Leardini, A., et al., *Validation of the angular measurements of a new inertial-measurement-unit based rehabilitation system: comparison with state-of-the-art gait analysis.* Journal of neuroengineering and rehabilitation, 2014. **11**(1): p. 136.