A prospective assessment of the progression of flexed-knee gait over repeated gait analyses in the absence of surgical intervention in bilateral cerebral palsy

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CITATION

O'Sullivan, Rory; French, Helen; Horgan, Frances (2022): A prospective assessment of the progression of flexed-knee gait over repeated gait analyses in the absence of surgical intervention in bilateral cerebral palsy. Royal College of Surgeons in Ireland. Journal contribution. https://hdl.handle.net/10779/rcsi.19419188.v1

HANDLE

10779/rcsi.19419188.v1

Abstract

Background: Flexed-knee gait is a common gait pattern associated with cerebral palsy (CP). It leads to excessive forces on the knee and is thought to contribute to pain and deformity. While studies have shown improvements in mid-stance knee flexion following surgery there remains a lack of prospective data on the progression of flexed-knee gait in the absence of operative intervention.

Research Question: Does knee flexion progress over repeated assessments in the absence of surgery in a prospectively assessed cohort with CP?

Methods: Inclusion criteria were a diagnosis of bilateral CP, knee flexion at mid-stance >19^0 and no surgery within one year of the first gait analysis. Gait analysis was carried out at six-month intervals (minimum of three and maximum of six assessments). The progression of knee flexion over repeated analyses was assessed. The association between changes in knee flexion between assessments and gender, age, GMFCS level, change in ankle dorsiflexion, change in height and change in weight was examined.

Results: Forty-eight participants met the initial inclusion criteria and 32 (GMFCS I=11, II=17, III=4) completed the minimum three assessments. Of the 32 included participants, 21 participants (66%) demonstrated decreased knee flexion at mid-stance (mean decrease 6.6^0±3.4^0 ; range 2.0^0 – 13.0^0) and 11 participants (34%) demonstrated increased knee flexion at mid-stance (mean increase 10.4^0±7.1^0 ; range 2.0^0 – 20.0^0). at one-year follow-up. Of these, 18 (56%) then demonstrated an overall decrease (mean 7.4^0 ± 5.1^0) in knee flexion between the first and last assessment with last follow-up at 1-2 years (n=3), 2-3 years (n=3) and 3-4 years (n=12). The majority of participants (78%) demonstrated episodes of both increasing and decreasing Knee flexion between individual assessments and further analysis found that only age was associated with this inter-assessment variability in knee flexion.

Significance: Flexed-knee gait is not always progressive in bilateral CP and demonstrated variability which was associated with age.

Keywords: cerebral palsy, crouch gait, knee flexion, kinematics, gait analysis

Introduction

Cerebral palsy (CP) is the most common cause of motor impairment in children [1] and the associated muscle tightness, weakness and impaired motor control often lead to difficulties during gait. There are numerous gait presentations associated with CP but excessive knee flexion in stance phase is one the most common pathological patterns [2]. This flexed knee posture during gait has been shown to increase the forces and demands on the knee joint [3, 4] and had been thought to increase the energy cost of gait [5]. Additionally, it has been assumed that without appropriate intervention, knee flexion progresses over time and for these reasons, the correction of flexed knee gait is a significant focus of surgical intervention in CP and a number of surgical techniques have been shown to improve knee kinematics in CP gait [6-9].

However, to date few studies have examined the natural progression of flexed-knee gait in bilateral CP in the absence of surgical intervention. A recent systematic review of the existing literature [10] found five studies meeting the selection criteria of repeated measures of knee flexion using 3-dimensional gait analysis (3DGA) with no intervening surgical intervention [11-15]. Four of the five included studies were retrospective cohort studies [11-14] and the fifth was a single participant case-study [15]. All four retrospective cohort studies examined knee flexion during stance phase at two time-points at follow-up times varying from one-year in a cohort of 30 participants[12] to 6.3 years in a cohort of 18 participants [14]. Despite the variability in both participant numbers and follow-up times, all four studies reported that the natural progression is towards increasing knee flexion over time. However, by reporting on knee flexion in stance on two occasions only, these four retrospective studies suggested a ‘straight line’ progression of knee flexion over time and therefore, neither individual progression over time or variation over a number of assessments could be ascertained. In contrast, the included single participant case-study [15] reported knee flexion in stance at yearly intervals for eight years which allowed variation over a number of gait analyses to be appreciated. In contrast to the four included retrospective cohort studies, this case study highlighted significant variation in knee flexion angle over repeated analyses and the single participant demonstrated an overall reduction in knee flexion between the first and last assessment. The authors of this case-study suggest that this overall decrease is not representative of all children with spastic CP but rather that the overall improvement was secondary to aggressive non-operative management, botulinum toxin, dedicated home exercise programme and post intervention rehabilitation. They also highlight a potential relationship between the variation in knee flexion over time and growth and report that between the ages of 9 and 13 changes in knee flexion in stance mirrored changes in body mass index (BMI) [15]. However, it is difficult to extrapolate more generally from this single participant case study and in particular the influence of factors such as GMFCS level and prior surgery, both of which are related to increased prevalence of crouch gait [2, 16, 17], cannot be appreciated.

While it has been highlighted that one of the difficulties in assessing the effectiveness of surgical intervention in CP is that studies tend to be small and retrospective [6, 18], it appears that the same issues relate to the study of the natural progression of CP gait and the need for larger, clinically based prospective studies of walking in CP has previously been highlighted [19].

The aims of this study were-

1. To prospectively examine the progression of, and variability in, flexed-knee gait over repeated assessment every six-months (to a maximum of six assessments) in a cohort of ambulant participants with bilateral CP
2. To examine how age, gender, prior surgical history, GMFCS level, change in ankle dorsiflexion and changes in height and weight influence variability in knee flexion at mid-stance.

Methods

The local host institution research ethics committee granted ethical approval for this study and written, informed consent was obtained from all parents/guardians. Inclusion criteria were a diagnosis of spastic, bilateral cerebral palsy GMFCS level I-III, age 4 to 17 years at the time of analysis and flexed-knee gait. Flexed-knee gait was defined as knee flexion greater or equal to two standard deviation above normal at mid-stance phase in at least one limb [20]. Based on a review of our laboratory database this equated to a mid-stance knee flexion value of greater or equal to 19^0. Participants were excluded if they had surgery within one year prior to the first gait analysis.

Potential study participants were identified from those attending for routine clinical gait analysis between December 2014 and February 2017. In addition, the gait laboratory database was used to identify participants who met the inclusion criteria up to two years prior to December 2014 and willing participants were subsequently invited back to the laboratory for research assessment. Participants then attended for 3DGA at 6-month intervals to a maximum of six assessments.

Three-dimensional kinematic data were captured at a rate of 200 Hz using a four-camera Codamotion cx1 active marker system (Charnwood Dynamics, Leicestershire, UK). Infrared markers were placed on each participant's lower limbs as per a modified Helen Hayes protocol [21] and all marker placement was carried out by a singe assessor to eliminate any inter-assessor error. All participants walked barefoot at a self-selected speed. Participants walked independently where possible. If independent gait was not possible data were collected while the participant walked with the assistance of two hands held in front by a physiotherapist as is standard practice in the gait laboratory.

A minimum of four walking trials was recorded for each participant and, reflecting clinical practice, one representative walking trial was chosen from these for further analysis. To avoid dependence between sides, only one side was chosen for analysis [22]. If only one limb of a participant met the objective criteria, only that limb was included [20]; if both sides met the inclusion criteria , the more involved limb was chosen for analysis [23].

Only those with three or more assessments were included as a minimum of three analyses were needed to establish if there was a pattern of overall increase or decrease in crouch over time.

The change in the median values of knee flexion at mid-stance between each of the six assessments was assessed using a non-parametric Kruskal-Wallis test. Knee flexion at mid-stance was plotted against age at each assessment for each of the included participants. The individual changes in knee flexion at mid-stance were then examined and the number of participants demonstrating an overall increase or decrease in knee flexion at mid-stance between their first and last assessments were reported. This was similarly reported between each of the six individual assessments. Change in the value of knee flexion at mid-stance was defined as any change greater than intra-rater error due to marker placement in knee flexion/extension kinematic graphs. Intra-rater error was assessed as part of the laboratories Clinical Movement Analysis Society UK and Ireland (CMAS) accreditation process and the value (1.13^0) represents the standard deviation of repeated measures determined as per previously reported protocols [24, 25]. The association between the changes in knee flexion at mid-stance between individual assessments and gender, age, GMFCS level, change in maximum ankle dorsiflexion in stance, change in height and change in weight was first examined using Spearman's rank correlations with significance was set at $p<0.05$. Those variables significantly correlated ($p<0.05$) with change in knee flexion were then used as predictor variables in a random coefficients regression model.

Results

From a total of 48 participants who met the initial inclusion criteria, 32 participants completed three or more assessments and so were included in the final analysis. A flow-chart outlining the number of child/adolescent participants assessed at each time point is shown in Figure 1. Reasons for not completing the full six assessments included those lost to follow-up (n=5), surgical intervention (n=18), became non-ambulant/full time wheel-chair user (n=3) and three participants completed less than three assessments during the study window.

Insert Figure 1 about here

At one-year follow-up after three assessments, 21 participants (66%) demonstrated decreased knee flexion at mid-stance (mean decrease $6.6^0 \pm 3.4^0$; range 2.0^0 – 13.0^0) and 11 participants (34%) demonstrated increased knee flexion at mid-stance (mean increase $10.4^0 \pm 7.1^0$; range 2.0^0 – 20.0^0). Of the 32 participants who completed the required three or more assessments, 18 participants (56%) demonstrated an overall decrease (mean decrease $7.4^0 \pm 5.1^0$; range 2.0^0 – 23.0^0) between the first and last assessment, with the last assessment at 1-2 years (n=3), 2-3 years (n=3) and 3-4 years (n=12). Thirteen participants (41%) demonstrated an overall increase in knee flexion at mid-stance (mean increase $11.6^0 \pm 10.4^0$; range 2.0^0 – 39.0^0), with the last assessment at 1-2 years (n=1), 2-3 years (n=6) and 3-4 years (n=6). Only one participant (3%) did not demonstrate a significant change (1.0^0) in the 3.6 years between their first and last assessment.

The individual changes in knee flexion at mid-stance are shown in Figure 2 which plots knee flexion at mid-stance versus age at each assessment for each of the 32 included participants. Figure 2 highlights that the majority of participants, (n=25, 78%), demonstrated episodes of both increasing and decreasing knee flexion at mid-stance between analyses while only three (9%) demonstrated a consistent increase in knee flexion at mid-stance across all included analyses and four participants (13%) demonstrated consistent decrease in this value.

Insert Figure 2 about here

A summary of the knee flexion at mid-stance along with participant descriptors at each of the six assessments is shown in Table 1 using means and standard deviations for normally distributed data or medians and inter-quartile ranges where not normally distributed. The median value of knee flexion at mid-stance did not change significantly across the six assessments (p=0.26). The numbers of participants who increased (>1.13^0 intra-rater error), decreased (>1.13^0 intra-rater error) or demonstrated no change (<1.13^0 intra-rater error) in knee flexion at each individual follow-up are also summarised.

Insert Table 1 about here

The 32 included participants had a total of 167 individual assessments and the 135 individual inter-assessment changes in Knee flexion at mid-stance were calculated. The Spearman rank correlation co-efficients summarising the association between the individual changes in Knee flexion and relevant variables are summarised in Table 2. There was a significant association between change in knee flexion at mid-stance and gender (rho=0.21, p=0.02) with males demonstrating increased variability. There was an inverse relationship between age and change in knee flexion (rho=-0.24, p<0.01) suggesting that younger participants demonstrated increased variability.

Insert Table 2 about here

Based on the correlations summarised in Table 2, both Age and Gender were therefore included in a random coefficients regression model. However, as gender was found not to contribute significantly to the model (p=0.07) it was removed as a variable so that the final model (Table 3) only included age.

Insert Table 3 about here

Discussion

In this prospective cohort study, flexed-knee gait in bilateral CP was found to both increase and decrease over time in the majority of participants and does not necessarily progress between assessments. The need for clinically based prospective studies of walking in CP has previously been highlighted [19] and the major strength of the current study is that gait was assessed prospectively every six-months in a cohort of participants with bilateral ambulant CP. This is in contrast to the existing literature, all of which is based on retrospective data [10]. This may explain the contrasting findings when comparing the current results to the previously summarised retrospective cohort studies [11-14], all of which report a mean increase in knee flexion over two repeated assessments. Retrospective studies are obviously limited to the gait data collected from those referred for clinical gait analysis. Referral for clinical gait analysis is often as a result of a deterioration in function, pain or to aid with planning of required intervention. It is perhaps not surprising therefore, that retrospective cohort studies based on such data all demonstrate a mean deterioration in gait between two analyses. By prospectively assessing knee flexion during gait, the current study also included those who may not have been referred for clinical gait analysis as their presentation was stable or no intervention was planned or felt necessary. Therefore, the prospective design of the current study is probably more representative of the population as a whole. However, by including only those with three or more assessments a number of participants who had surgery or became non-ambulant were excluded from analysis which potentially skewed the current study cohort and this may also have contributed to the discrepancy in findings. Of the 18 participants who had surgery during the study data collection period, 12 were excluded from analysis and all 3 participants who became non-ambulant were excluded (Figure 1). It is likely that at least some of these participants would have demonstrated an increase in crouch but in spite of this the current results clearly highlight that flexed-knee gait cannot always be assumed to be progressive in bilateral CP.

By including those with three or more analyses, this study is the first to document the variability in knee flexion between intermediate assessments in a cohort with bilateral CP. Only one single participant case study has previously demonstrated this variability [15] and the current results in a larger study cohort suggest that this is the norm in children and adolescents with bilateral CP. Butler's case study [15] suggested that the change in knee flexion angle over time may have been related to growth as assessed using BMI. The current results do not support this and there was no correlation between change in knee flexion across intermediate assessments and changes in height or weight. Instead, age was found to be the most significant contributor to the variability in knee flexion angle with younger age being associated with increased variability in 3DGA assessment of crouch gait. That gait is more variable in younger participants is probably consistent with what is known in relation to natural changes in spasticity levels and gross motor function both of which increase most rapidly up to the age of six or seven years before tapering off [26-29]. In light of these significant, naturally occurring changes in younger individuals with CP, it is not surprising that gait analysis measures of flexed-knee gait were more variable in younger participants in this study. While gender did not appear to be an independent contributory variable in the final random co-efficients model, initial spearman correlations suggested that male gender was associated with increased variability in measures of knee flexion during gait. Therefore the impact of gender on variability in flexed-knee gait measures in CP is somewhat unclear which is consistent with previous literature. A critical review published in 2016 [30] concluded that there was limited evidence that gender had an effect on neuromotor outcome. However, previous studies have reported that females demonstrate better results following both operative and non-operative intervention and that males had a higher incidence of lower limb deformity that was unresponsive to non-operative intervention and suggested that this may need to be considered when planning intervention or when assessing the outcome of intervention [31, 32].

There are a number of limitations to be considered when interpreting the results of this study. Flexed-knee gait was defined purely based on knee kinematics and we did not consider ankle kinematics in defining the study cohort . For this reason the term flexed-knee gait was used rather than crouch gait. However, defining the cohort solely based on knee kinematics appears to be in keeping with current literature and while definitions of crouch gait have included both ankle plantarflexion [33] and dorsiflexion [16, 34] more recent literature has defined crouch gait based on a flexed knee in stance regardless of ankle position [35, 36]. The current results found that there was no correlation between change in knee flexion during gait and change in ankle dorsiflexion (rho=0.09; p=0.31) which potentially supports defining crouch gait based on knee position only but this would need to be examined in a larger, more diverse study cohort. As would be expected in a study of ambulant CP, the majority of participants were GMFCS-levels I-II with only a limited number of those classified as GMFCS III. It has previously been shown that the prevalence of crouch gait increases with GMFCS level [17] and while this study suggests that the inter-assessment variability in measure of knee flexion during gait is not related to GMFCS level the generalizability of the current results to more involved participants, particularly GMFCS level III is limited. Similarly, the study cohort included some participants who had previous orthopaedic surgery and again, while the prevalence of flexed-knee gait increases with previous surgery [2, 16], this was not related to inter-assessment variability in knee flexion. However, this study did not attempt to analyse, or control for, the type or amount of prior orthopaedic surgery. Likewise, non-operative interventions were not controlled or studied. Participants were recruited nationwide and so, the type and frequency of non-operative management would have varied. Despite this, the vast majority of included participants demonstrated variability in knee flexion and also overall improvement in knee flexion between the first and last assessment but we are unable to comment on how non-operative interventions influence the progression of crouch. Finally, while the current results show that variation in 3DGA assessment of flexed-knee gait is the norm, before interpreting these changes as true changes consideration must be given to expected errors in knee flexion/extension data due to marker placement errors. Typically these marker related errors are of small magnitude ($<5^0$) [37] and the current results suggest that changes beyond this are to be expected due to natural variation and changes of this larger magnitude should be taken into account when considering true deterioration in gait or when assessing the impact of surgical intervention.

This study has shown that in the absence of surgical intervention, when assessed at six-month intervals, there was significant variation in measure of flexed-knee gait in individuals with bilateral CP. Furthermore, flexed-knee gait, as quantified using the value of Knee flexion at mid-stance, did not always progress over time when considering the values at first and last assessments. The variation in 3DGA measure of knee flexion in stance across intermediate assessments was primarily related to age and younger individuals with CP show increased variation. These findings should be considered in the context of recommending treatment or intervention based on gait analysis and also in assessing the outcomes of intervention.

Acknowledgements.

The lead author is a research fellow funded by the Health Research Board of Ireland [HPF-2014-650].

Conflict of interest statement

The authors have no interests which might be perceived as posing a conflict or bias.

References

1. Oskoui, M., F. Coutinho, J. Dykeman, N. Jette, and T. Pringsheim, *An update on the prevalence of cerebral palsy: a systematic review and meta-analysis.* Dev Med Child Neurol, 2013. **55**(6): p. 509-19.
2. Wren, T.A., S. Rethlefsen, and R.M. Kay, *Prevalence of specific gait abnormalities in children with cerebral palsy: influence of cerebral palsy subtype, age, and previous surgery.* J Pediatr Orthop, 2005. **25**(1): p. 79-83.
3. Steele, K.M., M.S. Demers, M.H. Schwartz, and S.L. Delp, *Compressive tibiofemoral force during crouch gait.* Gait Posture, 2012. **35**(4): p. 556-60.
4. Steele, K.M., M.M. van der Krogt, M.H. Schwartz, and S.L. Delp, *How much muscle strength is required to walk in a crouch gait?* J Biomech, 2012. **45**(15): p. 2564-9.
5. Rose, J., J.G. Gamble, J. Medeiros, A. Burgos, and W.L. Haskell, *Energy cost of walking in normal children and in those with cerebral palsy: comparison of heart rate and oxygen uptake.* J Pediatr Orthop, 1989. **9**(3): p. 276-9.
6. Galey, S.A., Z.F. Lerner, T.C. Bulea, S. Zimbler, and D.L. Damiano, *Effectiveness of surgical and non-surgical management of crouch gait in cerebral palsy: A systematic review.* Gait Posture, 2017. **54**: p. 93-105.
7. Putz, C., S.I. Wolf, E.M. Mertens, A. Geisbusch, S. Gantz, F. Braatz, et al., *Effects of multilevel surgery on a flexed knee gait in adults with cerebral palsy.* Bone Joint J, 2017. **99-b**(9): p. 1256-1264.
8. Healy, M.T., M.H. Schwartz, J.L. Stout, J.R. Gage, and T.F. Novacheck, *Is simultaneous hamstring lengthening necessary when performing distal femoral extension osteotomy and patellar tendon advancement?* Gait Posture, 2011. **33**(1): p. 1-5.
9. Boyer, E.R., J.L. Stout, J.C. Laine, S.M. Gutknecht, L.H. Araujo de Oliveira, M.E. Munger, et al., *Long-Term Outcomes of Distal Femoral Extension Osteotomy and Patellar Tendon Advancement in Individuals with Cerebral Palsy.* J Bone Joint Surg Am, 2018. **100**(1): p. 31-41.
10. O’Sullivan, R., F. Horgan, T. O’Brien, and H. French, *The natural history of crouch gait in bilateral cerebral palsy: A systematic review.* Research in Developmental Disabilities, 2018. **80**: p. 84-92.
11. O'Sullivan, R., M. Walsh, D. Kiernan, and T. O'Brien, *The knee kinematic pattern associated with disruption of the knee extensor mechanism in ambulant patients with diplegic cerebral palsy.* Clin Anat, 2010. **23**(5): p. 586-92.
12. Gough, M. and A.P. Shortland, *Can clinical gait analysis guide the management of ambulant children with bilateral spastic cerebral palsy?* J Pediatr Orthop, 2008. **28**(8): p. 879-83.
13. Bell, K.J., S. Ounpuu, P.A. DeLuca, and M.J. Romness, *Natural progression of gait in children with cerebral palsy.* J Pediatr Orthop, 2002. **22**(5): p. 677-82.
14. Rose, G.E., K.A. Lightbody, R.G. Ferguson, J.C. Walsh, and J.E. Robb, *Natural history of flexed knee gait in diplegic cerebral palsy evaluated by gait analysis in children who have not had surgery.* Gait Posture, 2010. **31**(3): p. 351-4.
15. Butler, E.E., K.M. Steele, L. Torburn, J.G. Gamble, and J. Rose, *Clinical motion analyses over eight consecutive years in a child with crouch gait: a case report.* J Med Case Rep, 2016. **10**: p. 157.

16. Rodda, J.M., H.K. Graham, L. Carson, M.P. Galea, and R. Wolfe, *Sagittal gait patterns in spastic diplegia.* J Bone Joint Surg Br, 2004. **86**(2): p. 251-8.
17. de Morais Filho, M.C., C.M. Kawamura, J.A. Lopes, D.L. Neves, O. Cardoso Mde, and J.B. Caiafa, *Most frequent gait patterns in diplegic spastic cerebral palsy.* Acta Ortop Bras, 2014. **22**(4): p. 197-201.
18. McGinley, J.L., F. Dobson, R. Ganeshalingam, B.J. Shore, E. Rutz, and H.K. Graham, *Single-event multilevel surgery for children with cerebral palsy: a systematic review.* Dev Med Child Neurol, 2012. **54**(2): p. 117-28.
19. Opheim, A., J.L. McGinley, E. Olsson, J.K. Stanghelle, and R. Jahnsen, *Walking deterioration and gait analysis in adults with spastic bilateral cerebral palsy.* Gait Posture, 2013. **37**(2): p. 165-71.
20. Ries, A.J. and M.H. Schwartz, *Ground reaction and solid ankle-foot orthoses are equivalent for the correction of crouch gait in children with cerebral palsy.* Dev Med Child Neurol, 2019. **61**(2): p. 219-225.
21. Kiernan, D., J. Hosking, and T. O'Brien, *Is adult gait less susceptible than paediatric gait to hip joint centre regression equation error?* Gait Posture, 2016. **45**: p. 133-6.
22. Dreher, T., D. Vegvari, S.I. Wolf, A. Geisbusch, S. Gantz, W. Wenz, et al., *Development of knee function after hamstring lengthening as a part of multilevel surgery in children with spastic diplegia: a long-term outcome study.* J Bone Joint Surg Am, 2012. **94**(2): p. 121-30.
23. Rha, D.W., K. Cahill-Rowley, J. Young, L. Torburn, K. Stephenson, and J. Rose, *Biomechanical and Clinical Correlates of Stance-Phase Knee Flexion in Persons With Spastic Cerebral Palsy.* PM R, 2016. **8**(1): p. 11-8; quiz 18.
24. Schwartz, M.H., J.P. Trost, and R.A. Wervey, *Measurement and management of errors in quantitative gait data.* Gait Posture, 2004. **20**(2): p. 196-203.
25. Kiernan, D., M. Walsh, R. O'Sullivan, D. Fitzgerald, and T. O'Brien, *Reliability of the CODA cx1 motion analyser for 3-dimensional gait analysis.* Gait & Posture, 2014. **39**: p. S99-S100.
26. Linden, O., G. Hagglund, E. Rodby-Bousquet, and P. Wagner, *The development of spasticity with age in 4,162 children with cerebral palsy: a register-based prospective cohort study.* Acta Orthop, 2019: p. 1-10.
27. Rosenbaum, P.L., S.D. Walter, S.E. Hanna, R.J. Palisano, D.J. Russell, P. Raina, et al., *Prognosis for gross motor function in cerebral palsy: creation of motor development curves.* Jama, 2002. **288**(11): p. 1357-63.
28. Hagglund, G. and P. Wagner, *Development of spasticity with age in a total population of children with cerebral palsy.* BMC Musculoskelet Disord, 2008. **9**: p. 150.
29. Hanna, S.E., D.J. Bartlett, L.M. Rivard, and D.J. Russell, *Reference curves for the Gross Motor Function Measure: percentiles for clinical description and tracking over time among children with cerebral palsy.* Phys Ther, 2008. **88**(5): p. 596-607.
30. Romeo, D.M., F. Sini, C. Brogna, E. Albamonte, D. Ricci, and E. Mercuri, *Sex differences in cerebral palsy on neuromotor outcome: a critical review.* Dev Med Child Neurol, 2016. **58**(8): p. 809-13.
31. Gough, M., R. Shafafy, and A.P. Shortland, *Does sex influence outcome in ambulant children with bilateral spastic cerebral palsy?* Dev Med Child Neurol, 2008. **50**(9): p. 702-5.

32. Zwick, E.B., M. Svehlik, T. Kraus, G. Steinwender, and W.E. Linhart, *Does gender influence the long-term outcome of single-event multilevel surgery in spastic cerebral palsy?* J Pediatr Orthop B, 2012. **21**(5): p. 448-51.
33. Perry, J., *Gait Analysis Normal and Pathological Function*. 1992: SLACK Incorporated.
34. Sutherland, D.H. and J.R. Davids, *Common gait abnormalities of the knee in cerebral palsy.* Clin Orthop Relat Res, 1993(288): p. 139-47.
35. Rozumalski, A. and M.H. Schwartz, *Crouch gait patterns defined using k-means cluster analysis are related to underlying clinical pathology.* Gait Posture, 2009. **30**(2): p. 155-60.
36. Kadhim, M. and F. Miller, *Crouch gait changes after planovalgus foot deformity correction in ambulatory children with cerebral palsy.* Gait Posture, 2014. **39**(2): p. 793-8.
37. McGinley, J.L., R. Baker, R. Wolfe, and M.E. Morris, *The reliability of three-dimensional kinematic gait measurements: a systematic review.* Gait Posture, 2009. **29**(3): p. 360-9.

Table 1 Characteristics of the included participants at each of the six assessments

	Assessment					
	1	**2**	**3**	**4**	**5**	**6**
Participants (n)	32	32	32	27	25	19
GMFCS (n)	I=11 (34%) II=17 (53%) III=4 (13%)	I=11 (34%) II=17 (53%) III=4 (13%)	I=11 (34%) II=17 (53%) III=4 (13%)	I=11 (41%) II=14 (52%) III=2 (7%)	I=11 (44%) II=12 (48%) III=2 (8%)	I=8 (42%) II=10 (53%) III=1 (5%)
Male (n (%))	20 (63%)	20 (63%)	20 (63%)	16 (59%)	14 (56%)	11 (58%)
Previous surgery (n (%))	9 (28%)	9 (28%)	9 (28%)	8 (30%)	8 (32%)	7 (37%)
Age (years)	10.7±3.8 (4.4 – 17.5)	11.4±3.8 (5.0 – 18.1)	12.1±3.8 (5.5 – 18.7)	12.7±3.8 (6.2 – 19.4)	13.7±4.0 (6.7 – 20.2)	14.5±4.1 (8.2 – 21.3)
Height (m)	1.39±0.21 (1.00 -1.76)	1.43±0.20 (1.08 -1.79)	1.46±0.19 (1.11 -1.79)	1.50±0.18 (1.15 -1.80)	1.53±0.17 (1.19 -1.80)	1.56±0.17 (1.25 -1.81)
Weight (kg)	37.3±14.6 (16.2–62.4)	39.5±15.1 (17.3–66.3)	41.5±15.2 (19.3–72.4)	44.6±16.6 (20.8–77.7)	47.5±17.5 (21.4–85.8)	48.8±18.1 (23.2–92.6)
Knee flexion at mid-stance (^{0})^	22.0±8.0 (19.0–46.0)	24.0±13.0 (11.0–47.0)	22.0±16.0 (7.0–47.0)	20.0±9.0 (8.0–62.0)	21.0±10.2 (-2.0–42.3)	23.0±14.0 (8.0–45.0)
Maximum ankle dorsiflexion in stance (^{0}) ^	10.3±12.9 (-24.0-23.0)	10.2±7.0 (-12.6-22.2)	11.6±10.3 (-22.1-29.1)	11.1±10.2 (-27.0-21.6)	8.7±6.7 (-11.1-27.7)	9.7±9.9 (-26.5-22.7)
Change in knee flexion at mid-stance*						
Increase >1.13^0 (^{0}) (mean±sd; n(%))	N/A	7.0±6.0^ 11(34%)	6.2±3.9 10(31%)	7.7±7.0^ 9(33%)	6.5±3.4 9(36%)	7.3±3.4 11(58%)
Decrease >1.13^0(^{0}) (mean±sd; n(%))	N/A	5.3±2.6 16(50%)	5.0±2.0^ 15(47%)	5.9±3.2 13(48%)	7.0±5.2 11(44%)	6.3±1.8 2(11%)
No Change (n(%))	N/A	5(16%)	7(22%)	5(19%)	5(20%)	6(32%)

GMFCS- Gross motor function classification system; sd-standard deviation; *An increase or decrease in knee flexion at mid-stance was defined as a change >1.13^0 (intra-rater error); ^median and interquartile range.

Table 2 Spearman's rank correlations between Change in knee flexion and relevant anthropometric and descriptive variables

	rho	**p-value**
Change in height (%)	0.11	0.20
Change in weight (%)	0.04	0.66
Change in maximum ankle dorsiflexion in stance	0.09	0.31
Age (years)	-0.24	**<0.01***
Gender (male: female)	0.21	**0.02***
GMFCS	0.10	0.23
Previous surgery (yes: no)	0.12	0.17

GMFCS-Gross Motor Function Classification System *Significant values in bold

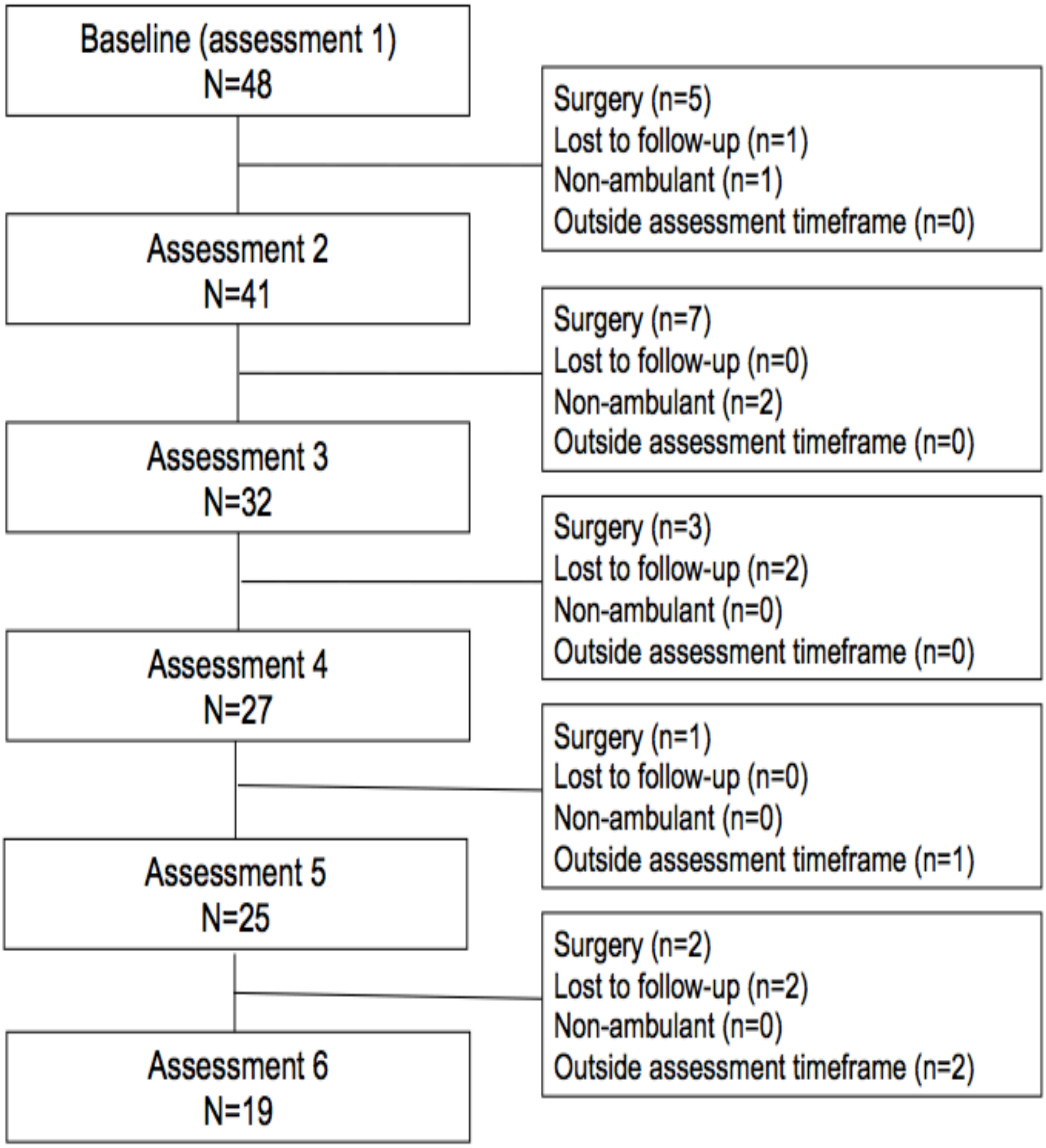
Table 3 Random co-efficients model of Change in knee flexion and Age

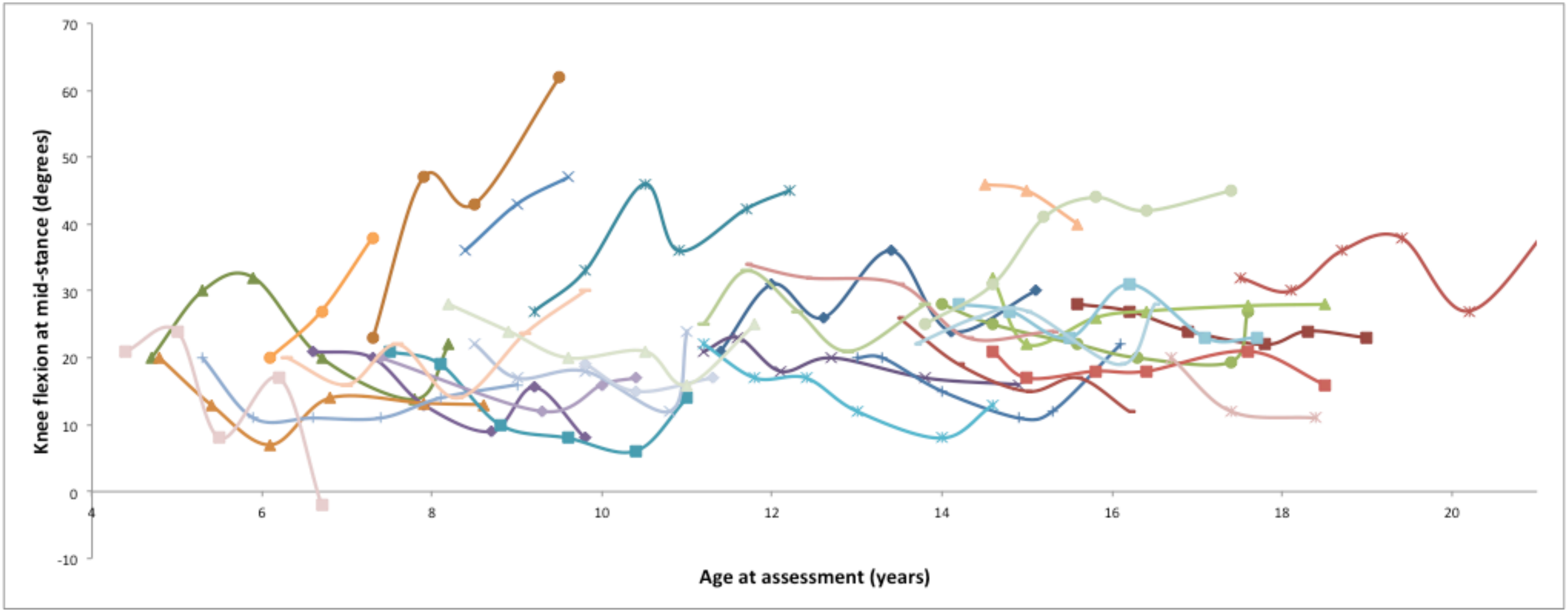
	Coefficient	Standard error	p-value
Change in knee flexion			
Age	-0.28	0.11	**0.01**
Intercept	8.50	1.36	**<0.01**

Figure Legends

Figure 1 Flow chart summarising the number of child/adolescent participants who had gait analysis at each of the six time-points and reasons for non-completion of the full number of analyses

Figure 2 Knee flexion at mid-stance at each assessment for participants with a minimum of three assessments (n=32)


Baseline (assessment 1)
N=48
Surgery (n=5)
Lost to follow-up (n=1)
Non-ambulant (n=1)
Outside assessment timeframe (n=0)
Assessment 2
N=41
Surgery (n=7)
Lost to follow-up (n=0)
Non-ambulant (n=2)
Outside assessment timeframe (n=0)
Assessment 3
N=32
Surgery (n=3)
Lost to follow-up (n=2)
Non-ambulant (n=0)
Outside assessment timeframe (n=0)
Assessment 4
N=27
Surgery (n=1)
Lost to follow-up (n=0)
Non-ambulant (n=0)
Outside assessment timeframe (n=1)
Assessment 5
N=25
Surgery (n=2)
Lost to follow-up (n=2)
Non-ambulant (n=0)
Outside assessment timeframe (n=2)
Assessment 6
N=19



Knee flexion at mid-stance (degrees)
70
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
Age at assessment (years)