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Sagittal gait patterns in cerebral palsy: The plantarflexor–knee extension couple index

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ABSTRACT

The identification of gait patterns in cerebral palsy offers a common language for clinicians and contributes to management algorithms. We describe a quantitative classification of sagittal gait patterns based on the plantarflexor–knee extension couple index. This consists of a scatter plot based on ankle and knee scores, and allows objective identification of the sagittal gait pattern.

Sagittal kinematic data from 200 limbs of 100 patients with bilateral spastic cerebral palsy were utilized to validate the algorithm against the assessment of a clinician with expertise in gait pattern identification. A dataset of 776 cerebral palsy patients, 1552 limbs, was used to compare the sagittal gait patterns against *k*-means statistical clustering. The classification was further explored with respect to the knee kinetics during the middle of stance and physical examination measurements of the gastrocnemius–soleus complex. Two supplementary materials (Appendices 2 and 3) provide in-depth discussion about statistical properties of the plantarflexor–knee extension couple index as well as its relationship with statistical clustering.

The plantarflexor–knee extension index achieved 98% accuracy and may be suitable for the computational classification of large patient cohorts and multicentre studies. The sagittal gait patterns were strongly related to *k*-means statistical clustering and physical examination of the gastrocnemius–soleus complex. Patients in crouch gait had normal soleus and gastrocnemius lengths but spasticity in the gastrocnemius. Patients in jump gait exhibited a short gastrocnemius and soleus and gastrocnemius spasticity. Patients in true equinus presented with a moderately contracted soleus and gastrocnemius and gastrocnemius spasticity. Patients in apparent equinus did not show abnormal physical examination measurements for the gastrocnemius–soleus complex.

1. Introduction

Davids et al. [1] described five sources of data to guide clinical decision-making for children with cerebral palsy. One of these, instrumented gait analysis, provides detailed information on the kinematics and kinetics of the joints of the lower limb. A typical instrumented gait analysis entails, for each limb, to analyze at least ten kinematics and kinetics curves. The interpretation of this data requires linking kinematic deviations with physical examination measurements, to define the gait impairments. The amount of data is invaluable to determine the appropriate treatment for a specific patient but may make it difficult to identify patterns and the construction of management algorithms.

Rodda et al. [2,3], described a semi-quantitative sagittal gait pattern classification for patients with bilateral spastic cerebral palsy (BSCP). That classification combined pattern recognition with quantitative kinematic data, and was based on an extension of earlier work by Rang et al. [4], Sutherland and Davids [5] and Miller et al. [6]. The Rodda classification described five groups: crouch gait, jump gait, apparent equinus, true equinus and mild gait (within normal limits in the sagittal plane). The classification in five groups applies to the limb and the asymmetric group is introduced when the two limbs of the same patient belong to two different classifications. Based on the above sagittal gait patterns Rodda et al. derived a management algorithm which specifies the dominant muscle groups to be targeted for treatment of spasticity

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or contracture and includes prescription of orthotics. This work has often been utilized to characterize the gait patterns of cohorts of patients (e.g. [7–11]).

Although the classification was based in part on quantitative data, it is also in part qualitative and subjective. It therefore requires the involvement of a clinician who is expert in gait analysis and in clinical assessment. This requirement may restrict the use of the Rodda classification to expert clinicians and may prohibit its application in large patient cohorts. Therefore the first purpose of this study was to propose and validate an algorithm to classify Rodda's sagittal gait patterns on a purely quantitative basis.

Quantitative algorithms based on clustering of the kinematic data have been proposed previously (e.g. [12–14]). These algorithms present optimal statistical properties but may be difficult to apply clinically and they have seldom been used in management algorithms. The sagittal gait classification by Rodda was not derived from statistical clustering but from years of clinical observations and the underlying statistical properties are unknown. Therefore the second purpose of this study was to compare the Rodda sagittal gait pattern classification with statistical clustering.

Sagittal plane kinematics at the ankle and knee in stance are mainly determined by the plantarflexion–knee extension couple [15]. The couple refers to the action of the gastrocnemius and soleus muscles, the ankle plantarflexors, to control both the advancement of the tibia over the foot and the knee kinetics in mid-stance. Spasticity or contracture of the gastrocnemius–soleus muscles in children with cerebral palsy is frequently present and will influence sagittal kinematics and kinetics. The third purpose of this study was to compare physical examination measurements of the plantarflexors with the sagittal gait patterns.

2. Material and methods

2.1. The plantarflexor–knee extension couple index

The plantarflexor–knee extension (PFKE) index calculates the distance of the patient's ankle and knee kinematics in mid-stance from normative data. The period of the gait cycle used to calculate the PFKE index is set between 20 and 45% of the gait cycle (see Appendix 1, in supplementary material, for a discussion about this choice). During this period, the knee extends while the ankle dorsiflexes, the knee moment changes from an extensor moment to a flexor moment allowing the quadriceps to cease contracting and the ankle to absorb power through the eccentric contraction of the gastrocnemius–soleus complex.

The PFKE index consists of two scores from the ankle and the knee. It is calculated as follow:

$$\mathrm{PFKE}^c = \frac{1}{45-20+1}\sum_{i=20}^{45}\frac{k_i^c-\mu_i^c}{\sigma_i^c}$$

where superscript c denotes the knee or ankle curve, subscript i denotes the time instant (in % of the gait cycle), k_i is the value of the kinematic curve at the i% instant of the gait cycle, μ_i is the value of the normal kinematic curve at the i% instant and σ_i is the value of the standard deviation from the normal kinematics curve at the i% instant. A PFKE index of (−3,2) means that, on average between 20 and 45% of the gait cycle, the ankle curve is three standard deviation below normal and the knee curve is two standard deviations above normal. The normal kinematics curves originated from 35 typically developed children (17 girls, 18 boys) with an age range of 6–17 years old.

Classification is based on the +1 or −1 values of the PFKE ankle and knee scores and is displayed on the PFKE scatter plot (Fig. 1 and Appendix 2 in the supplementary material). We define d_{PFKE} as the minimum 1 − D distance of one point to the other gait patterns. A large value for d_{PFKE} means the point is located far from all the other gait classifications and therefore specific to the gait pattern it belongs to.

Validation of the classification algorithm was performed by comparing the classification by the algorithm to classification by a clinical expert (J.R.) in a study of 200 lower limbs, in 100 patients with BSCP. Kinematic data from patients diagnosed with BSCP were randomly selected from our database. Accuracy of the classifier was expressed as the percentage of true classifications divided by the number of limbs assessed.

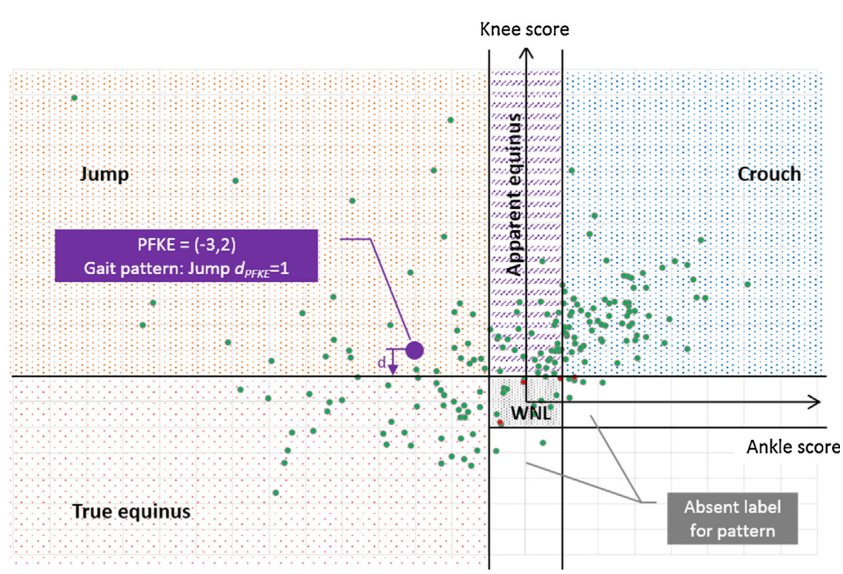

Fig. 1. The plantarflexor–knee extension scatter plot, with the ankle score in X and knee score in Y, for N = 200 limbs. The lines, corresponding to the 1 or −1 value for the ankle and knee scores, separate the sagittal gait patterns. The central section of the PFKE plot corresponds to the within normal limit (WNL) or mild sagittal gait pattern. An example for a PFKE index of (−3,2) is provided. This point corresponds to the jump gait pattern and is at a minimum distance d_{PFKE} = 1 to the nearest gait pattern (true equinus). The validation dataset is overlayed on the plot. Points were coloured in green if the automatic and expert classifications agreed and red if they disagreed. It can be noticed than only 4 points were misclassified and those were very close to the line between two classifications. This is confirmed by an average d_{PFKE} for those 4 points of 0.2. Eight points were located in areas of the plot without a labelled gait pattern. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)