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ON THE ANALYSIS OF CYCLIC HUMAN MOVEMENT

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INTRODUCTION

The detection of a single point within the gait cycle is fundamental to the analysis of human gait data. By selecting a reference point common to all cycles, the timing of the cycle can be temporally normalized and various stages of gait meaningfully compared.

Traditionally, in human gait research, heel-strike has been used to identify the temporal biomechanical reference point from which the relative timing of all events is measured. Consequently, identifying accurate, practical and cost-effective solutions for the detection of heel-strike has been the subject of much research and review (*e.g* [1]).

New methods of heel-strike detection are usually tested against the gold standard of a force plate embedded in the floor. Results are presented as mean error and standard deviation relative to the results obtained from the force plate (*e.g* [2]), and the method deemed successful if both the mean error and standard deviation are regarded as "low enough".

Past literature has yet to consider the effects of gait normalisation on measures of variability or provide appropriate objective methods for calculating the required accuracy of an event detection algorithm.

This study aims to (i) investigate the various unintended effects that temporal normalisation, can have on data analysis (ii) specify a novel guideline for the required accuracy of new gait event detection methods, and (iii) motivate a change in paradigm from the traditional normalisation of gait to a novel multidimensional "free path" model.

METHODS

Data from three different gait studies were combined.
The "**Fatigue**" trial, investigated 12 trained long distance runners, while running quickly, both barefoot and shod, before and after fatiguing bouts of exercise. A total of 482 gait cycles were measured.
The "**PFP**" trial, measured 16 subjects, who were rehabilitated from recent Patello Femoral Pain Syndrome, and 16 healthy controls, performing barefoot and shod running at a self-paced comfortable jog. A total of 301 gait cycles were measured.
The "**Arthroplasty**" trial, measured 4 participants, who had undergone uni-lateral full knee arthroplasty, after conventional rehabilitation and again after an additional rehabilitation intervention, performing a simple walk. A total of 80 gait cycles were measured.
Each study was approved by the UCT Faculty of Health Sciences' Human Research Ethics Committee.
Lower body joint kinematics were measured using a Vicon MX motion capture system implementing a modified Helen Hayes marker set [3].

RESULTS AND DISCUSSION

Using one variable for cyclic point identification – Traditionally the arbitrary start and end/re-start of a gait cycle can be defined using any cyclic gait variable, which has a feature that can be repeatably identified, for example the local minima shown in Figure 1. Using a feature that corresponds to an intuitive part of gait, such as using the traditional "heel-strike", can be beneficial, although not all gait styles include a heel-strike [4]. Once identified all the measured gait variables are splined into percentage of gait between two successive start/end points.

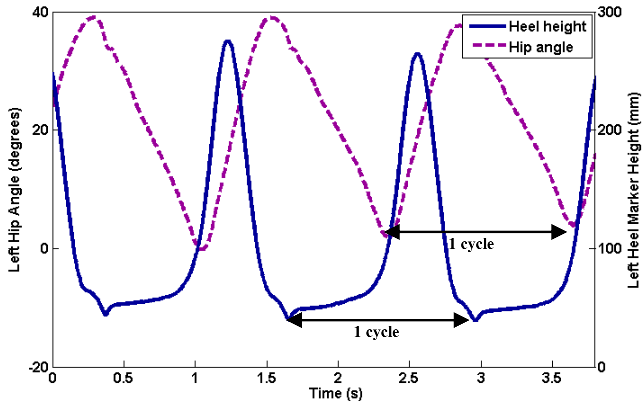

Figure 1 Vertical height of the heel marker and hip flexion/extension angle over time for a subject from the "Arthroplasty" trial, demonstrating how any repeatably identifiable feature of a cyclic time series, such as a local minimum, can be used to temporally normalise the gait cycle.

Calculating the required accuracy of the timing reference – Applying statistical inferences to the individual case can be inappropriate [5]. Measuring the accuracy of a cyclic event detection method by using mean error and standard deviation from the gold standard, as done in the literature, leaves the researcher exposed to massive error in the individual case. Absolute maximum error would be a more appropriate measure. Below we present a method for calculating the maximum tolerable temporal error in event detection.

The maximum error is dependent on the nature of the investigation. Ultimately, if any variable can change by more than an acceptable amount, within the error period of the event detection method, then a more accurate method is required.

For example the highest rate of change (ROT) was achieved for the toe marker in the direction of motion consistently for the three studies. This variable showed the ROT of approximately 10, 9 and 4.2 m/s for the "Fatigue", "PFP" and "Arthorplasty" trials respectively. If, hypothetically, the research could only tolerate a maximum error (ME) of 10 mm for marker motion in each case, then the maximum temporal error (MTE) of a cyclic reference point is given by the equation: MTE = ME/ROT, and in this case, would be 1, 1.1 and 2.4 ms respectively.

The effect of single point cyclic identification on the measure of variability of gait – The traditional normalisation method works on the assumption that gait variables have a constant phase relationship and only vary in amplitude. However, changes in phase do occur and unknowingly present as changes in amplitude.

By definition, the features used to identify the cyclic point show little to no variability at the point itself. One can imagine the gait cycle as a spring with its ends anchored. The middle is free to stretch and vary from cycle to cycle, but the ends are fixed. The closer to the ends a point on the spring is, the less variability is allowed. Hence, the distance from the anchor point effects the amount of variability allowed in the variables used to create the anchors, and those strongly correlated to them.

Providing a measure of the effect of this type of normalisation on measures of variability and phase is impossible within the current paradigm, since it's the paradigm itself that causes the error. A new model is proposed bellow that allows for full freedom of all variables, both in phase and amplitude. Regardless, researchers must be cautious when investigating variability over the gait cycle using the normalisation model.

A "free path" approach to gait cycle analysis –
One can demonstrate the cycling nature of gait by plotting two variables against each other producing a free path tracing out a closed loop as shown in Figure 2. Here the variables are free to change in both in amplitude and phase equally at every point in the cycle. The path itself is a fingerprint for that type of gait cycle (for the variables used) and can be used to observe and calculate the differences between two gait styles as is often required in research.

There is no reason to limit the "free path" concept presented here to two variables and it can be extended to any number of hypothetical orthogonal axes including more and more variables to draw a complete picture of gait in one "image".

The variability of the position of the loop at any one point from cycle to cycle represents a measure of how appropriate that point is as a reference for normalising gait (*i.e.* how much information would be lost if that point were to become fixed). In this case low variability would translate into high repeatability both in terms of amplitude and phase. Incidentally, the overall variability of each of the variables in Figure 2 increases when we add the other two trial types (p values < 10^{-15}). This provides evidence that techniques, that identify repeatable points for one trial type, may not have external validity outside of that group and may suffer from "over fitting", often seen in pattern recognition algorithms (see [6] for more information).

Methods to calculate the mean and confidence intervals of multiple free paths are not freely available. Here we have "cheated" and normalised the gait prior to calculating the means, thus causing this analysis to suffer from the same problems identified above. Ideally no normalisation is required.

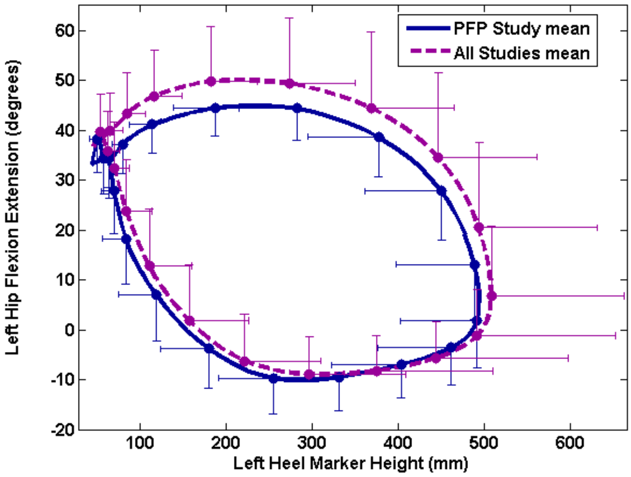

Figure 2 Vertical heel marker height against hip flexion/extension plotted for the combined cycles of the "PFP" study and for the combined cycles of all the studies together. Vertical and horizontal standard deviations are shown at 5% of gait cycle intervals.

CONCLUSIONS

The above demonstrations illustrate four key conclusions. Firstly, event detection algorithms should report absolute error, and those making use of them should calculate if this error is tolerable using the method described. Secondly, methods of gait event detection should be thoroughly checked for external validity when presented or used. Thirdly, those researching variability and phase in gait should be aware of the effects of temporal normalization. Finally, the "free path" paradigm does not suffer from the adverse effects introduced by normalisation, provides insight into the variability of gait and allows for the continuous analysis of multiple simultaneous variables.

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