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Principal component analysis of the power developed in the flexion/extension muscles of the hip in able-bodied gait

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Abstract

This study was undertaken to demonstrate how principal component analysis (PCA) can be used: (a) to detect the main functional structure of actions taken by hip extensors and flexors during two consecutive gait cycles of able-bodied subjects, and (b) to determine whether or not symmetrical behaviour exists between right and left hip muscle power activity. Twenty young, healthy male subjects walked along a 13 m path at a freely-chosen speed. Applying curve structure detection methods such as PCA to walking patterns can provide insight into the functional tasks accomplished by the lower limbs of able-bodied and disabled subjects. PCA was applied as a classification and curve structure detection method to hip sagittal muscle power calculated for the right and left lower limbs. Over 70% of the information provided by the first four principal components (PCs) was chosen for further biomechanical interpretation. PC1 for both right and left sides mainly described the action taken by the hip extensors/flexors corresponding to the vertical component of ground force on the respective limbs during mid-stance. Propulsion and limb preparation were identified as the second and third tasks attributed to right hip muscle power, while between limb co-ordination was recognised as the second and third functional tasks of the left hip extensors/flexors. Balance was identified as the fourth main functional contribution of the hip extensors/flexors at the right limb while for the left limb, these muscles were mainly responsible for preparing the limb to enter into new gait cycle. PCA was able to identify the four main functional contributions of hip sagittal muscle power during able-bodied gait. PCA was also able to examine the existence of functional asymmetry in gait by highlighting different task priorities at the hip level for the right and left lower limbs.

Keywords: Biomechanics; Gait pattern analysis; Principal component analysis

1. Introduction

Advanced medical technology provides kinematic and kinetic information which is often a function of time or position. To characterise able-bodied [1,2] or pathological [3–5] gait, processing the data obtained frequently consists of obtaining peak or zero crossing values of various curves. However, the characteristics of the curves were analysed in only a few able-bodied [1,6–8] and disabled [5,9,10] gait studies. In a gait study of 214 able-bodied subjects [8], force generation was characterised by marked population variability, step-to-step consistency and symmetry of the forces generated by each foot. Shiavi et al. [11] examined the variability and changes in gait patterns as speed increased. They found that the fundamental muscle activity phases never changed but the relative amplitudes of the phases were modulated. With hip sagittal muscle power data, Winter and Eng [6] characterised the main actions of the hip during the stance phase, namely balance, support and propulsion. Laassel et al. [12] studied the variations of the femur angle and the knee and ankle flexion–extension angles of able-bodied gait patterns. Using ground reaction forces derived from 50 able-bodied subjects,

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Loslever et al. [13] proposed a general methodology to analyse hip, knee and ankle angle excursions during gait. These investigations were basically descriptive rather than quantitative.

Although describing walking patterns provides an overall impression of lower limb behaviour, in the absence of an adequate statistical analysis, gait interpretation becomes extremely difficult and confusing rather than being more informative. In the last two decades, different multivariate statistical approaches which facilitate interpretation of the data based on variance estimation were applied to gait data [2,3,14–17] and Principal Component Analysis (PCA) is one of them. Although it has only been used in a few gait studies [2,5,7,16,18–21], it can explain much of the variance in the data with relatively few factors or principal components (PCs) [22]. In a study of 211 patients with hip diseases [17], a gait evaluation plan was suggested based on the results obtained from PCA of five parameters (joint angular displacement, ground reaction forces, trajectories for a point of force application, temporal and distance factors). In another gait study, PCA was carried out on 32 variables of ten major muscles of the lower extremity of 35 able-bodied subjects. The results showed that the highest weighted values in each PC were associated with the parts of the gait cycle where variability between individuals was most important [21]. Using the factor analysis technique, which in principle is similar to PCA, Davis and Vaughan [16] identified loading response, propulsion and balance as the major characteristics of phasic coactivity of 16 muscles during the gait cycle. Olree and Vaughan [23] performed similar statistical analyses on data obtained from both lower limbs and added a co-ordinating factor to assess muscle phasic coactivity. In 1994, Mah and colleagues [18] applied PCA to reduce the three-dimensional (3D) angular movement of six normal subjects with minimal loss of information. PCA was also used to evaluate peak values. Sadeghi et al. [2] applied PCA as a data reduction and data identification method on 54 spatio-temporal and kinetic parameters calculated for each lower limb. They detected asymmetry between right and left lower limbs in able-bodied gait. Recently, Olney et al. [5] used PCA on 40 spatio-temporal, kinematic and kinetic parameters obtained from 31 stroke patients to reduce redundant information. The first three PCs were found to be correlated mainly with speed, gait symmetry and postural strategy. In summary, PCA has been applied to gait mainly as a tool to reduce redundant information or for parameter identification [2,5,7,16,18–21] using peak or zero crossing values.

Our hypothesis was that PCA could be used to characterise the main features of continuous gait data in order to explain the functional tasks of the lower limbs in a gait cycle. Our second hypothesis was that differences between right and left hip muscle power activity could be detected by the PCA method. To explore these two assumptions, data from the sagittal plane were chosen since the major portion of muscle activity occurs in this plane [24]. Hip muscle power data were used because a wide variety of relatively common pathological conditions affect the hip [25,26] and because of its multifunctional task, particularly in compensating for the lack of normal functional task at the ankle joint when amputee gaits are investigated [27]. The main objective of this study was to demonstrate how PCA can be used: (a) to detect the main functional structure of actions taken by hip extensors and flexors during two consecutive gait cycles of able-bodied subjects, and (b) to determine whether or not symmetrical behaviour exists between right and left hip muscle power activity.

2. Methods

2.1. Subjects

The 20 young, healthy male subjects participating in this study had an average age of 25.3 (±4.1) years and height of 1.770 (±0.057) m and their average mass was 80.6 (±13.8) kg. They had no previous history of orthopaedic ailments, such as a recent injury or surgery, which could affect their walking pattern. Subjects who had limb length discrepancies between right and left of 0.5 cm or more were excluded from the study.

2.2. Testing procedure

2.2.1. Data collection

A 3D seven segment model consisting of the trunk, thighs, shanks and feet was defined using 20 reflective markers with a diameter of 2.5 cm. For each foot, markers were placed over the lateral malleolus, the heel and the lateral border of the fifth metatarso-phalangeal joint, while markers were placed over the apex of the lateral epicondyle and the mid-lateral side of the tibias to locate the shanks. Markers were also put over the mid-lateral side of the thighs and the greater trochanter to define the thighs. For the pelvis, markers were put over the anterior superior iliac spines and crests of ilium. The pelvic markers as well as markers put over the lateral border of the shoulders identified the trunk. To calculate motion in the joint co-ordinate system, measurements were taken between the external markers and the estimated joint centre of rotation of each lower limb. Bilateral kinetic gait data were assessed with an eight video-based camera system (90 Hz) synchronised to two AMTI force plates (360 Hz). Four cameras were placed on each side of the subject at an average distance of 4.5 m and located along an arc of about 120° to cover two consecutive strides. Subjects were asked to walk at a self-determined pace along the walkway and step on the force plates.

2.2.2. Data analysis

The Direct Linear Transformation software from the Motion Analysis Expert Vision system was used to reconstruct the image markers into three-dimensional coordinates. A fourth order zero-phase lag Butterworth low-pass filter was applied to reduce the noise in the video data (cut-off frequency: 6 Hz) and force data (cut-off frequency: 30 Hz). Body segment parameters, kinematic and force plate data were used in an inverse dynamic approach. Instantaneous muscle power was obtained as the product of the net muscle moment and the joint angular velocity at the hips in the sagittal plane on two consecutive gait cycles. The power bursts were labelled according to Eng and Winter [24]. The first letter refers to the joint and the number indicates the sequence of the power burst. The second letter identifies the plane of motion. For example, H1S corresponds to the first peak power or energy burst of the hip in the sagittal plane. Data were normalised with respect to body mass and by a curve registration technique [28] to reduce intersubject variability.

2.2.3. Statistical analysis

PCA as a classification and data structure detection method [29,30] was applied to the hip sagittal muscle power curves to identify the important features of data variation. Five steps were involved in the PCA application. The first consisted of finding the covariance matrix of the original parameters. Here, the matrix consisted of 20 rows (one row for each subject) for the sagittal displacement of hip joint and 101 columns presenting gait cycle in percentages. The second step was to choose the number of PCs which should be retained for further analysis. The eigenvalues indicated how many components were important in conveying most of the major information hidden in data. Based on the Kaiser criteria [31], the eigenvalues that accounted for more than 1% of the variance could be applied for further data interpretation. However, in reality, the first few PCs accounted for the main parts of the data variations suggested for analysis [29]. In this regard, the first four principal components which explained over 70% of the variance were retained. The fourth step was to choose and perform an appropriate type of rotation on the PCs to maximise the variation leading to a more quantitative interpretation of the data [32]. Varimax rotation was used to achieve the basic structure in a set of data by rotating the PC axes. The last step was to describe the PC to generate a meaning of what was being measured. To facilitate interpretation of the PCs, the parameters (here each instant of the gait cycle) which had the highest correlation with each PC [30,5] (called factor loading) were usually used. In this instance, a factor loading higher than 0.60 was used for further biomechanical interpretation. According to what each representative curve describes, names were given to the PCs. Significant differences between peak parameters were determined using Student's *t*-test for paired data with a $P<0.05$ threshold.

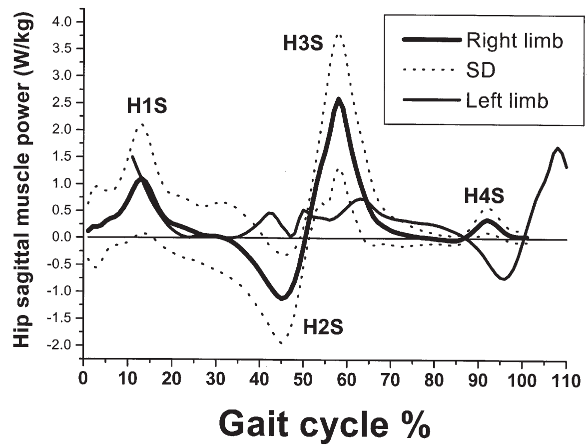

Fig. 1. Mean of hip sagittal muscle power curves developed at the right (thick line) and left (thin line) lower limb by 20 able-bodied subjects. The overlaid dashed line represents one SD from the mean for the right limb muscle power.

3. Results

The average and standard deviation (SD) of the mechanical muscle power developed at the hips in the plane of progression during the gait of 20 subjects are presented in Fig. 1. All the hip sagittal muscle powers of our subjects are similar to those of Winter and Eng [6]. Left-sided data (for both the power and principal components) are plotted relative to the % gait cycle of the right side. The thick line represents the hip sagittal muscle power developed at the right limb, while the thin line shows the simultaneous walking stride at the hip level of the left limb. The SD for the right limb is represented by dashed line and the SD for the left side is excluded for clarity.

Table 1 shows the mean peak muscle powers (±SD) obtained at four different phases during the gait cycle. Though the primary concern in this study was to identify

Table 1
Mean peak (±SD) values of hip sagittal muscle power in four phases of the gait cycle

Gait cycle	Power burst (W/kg)	
	Right limb	Left limb
Hip extensors (H1S)	1.15±1.02	0.89±0.76
Hip flexors (H2S)	−1.15±0.82	−0.76±0.68
Hip flexors (H3S)	2.63±1.25[a]	2.01±0.88[a]
Hip extensors (H4S)	0.36±0.24	0.43±0.30

[a] Indicates significant differences ($P<0.05$) between right and left.

the main structure of the continuous gait data, the peak hip sagittal muscle powers were reported to provide an overall impression of the hip sagittal muscles activity. The peak values for all four power bursts are lower at the left side than the right, and no significant differences were measured between the right and left limbs except at the pull-off (H3S).

The eigenvalues which show the variance extracted by each PC for the right and left hip sagittal muscle power curves during two consecutive gait cycles are presented in Fig. 2. The *Y* axis shows the fraction of the extracted variance (%), while the *X* axis shows the number of the representative curves that describe almost all the information. The first four representative muscle power curves which covered 78% and 70% of the hidden information in the original curves of the right and left lower limbs were retained for further analysis and are presented in Fig. 3. The fifth and higher PCs, which accounted for the remaining variations, were not taken into consideration since they presented random variations [5,16] which are difficult to interpret.

As was expected, the first representative curve (PC1) calculated at the right (solid line) and left (dashed line) hips accounted for the largest possible variance extracted from the variable (Fig. 3a). Comparatively, PC1 of the right and left hip sagittal muscle power curves extracted 40% and 38% of the total variance. On the right limb, a factor loading greater than 0.60 is distributed throughout the mid-stance including single limb support and double support (10–50% of the gait cycle (GC)). A higher factor loading was observed at the left limb (10–40% of GC) and relates to the action taken by the hip flexors and extensors during single limb support.

The second PC for the right hip accounted for 18% of the variation from the remaining variability. The negative and highly significant factor loading values in this component were spread throughout the pull-off and early and mid swing phases (55–80% of GC) as shown in Fig. 3b. At the left hip, PC2 demonstrated 13% of the information, while the highest factor loadings were distributed throughout the double support phase (40–50% of GC).

For the right limb, PC3 accounted for 12% of the remaining variations and it was orthogonal to all previously extracted PCs (Fig. 3c). In this representative curve, the higher factor loading was distributed during

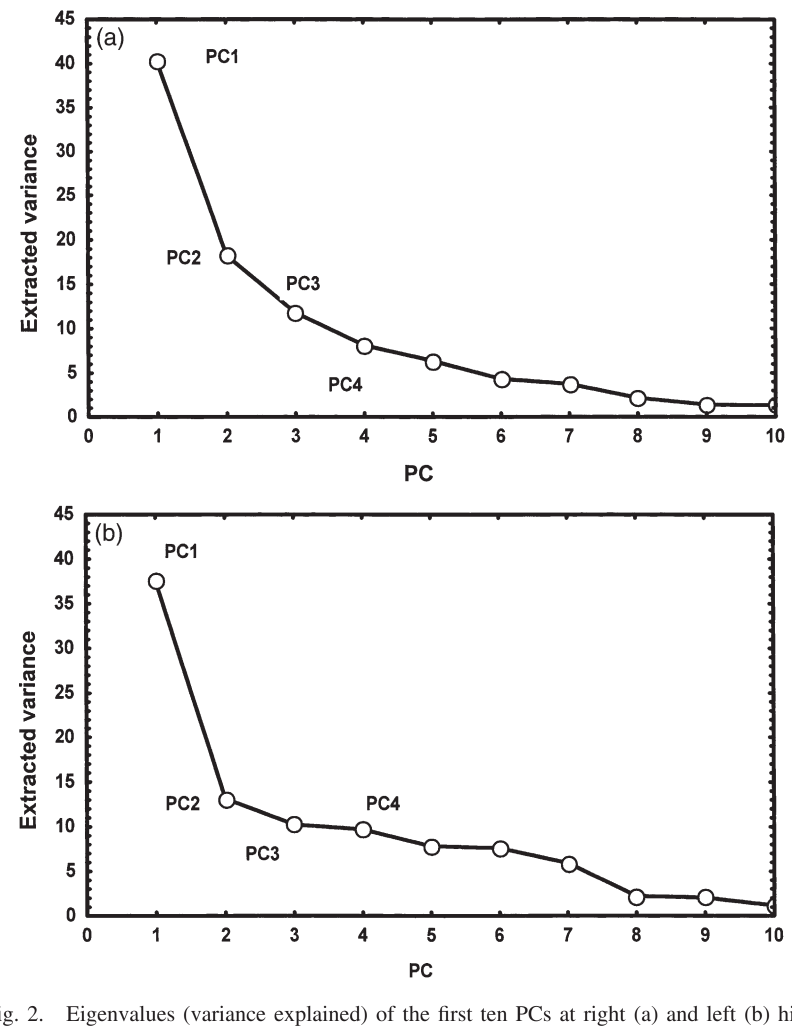

Fig. 2. Eigenvalues (variance explained) of the first ten PCs at right (a) and left (b) hips.

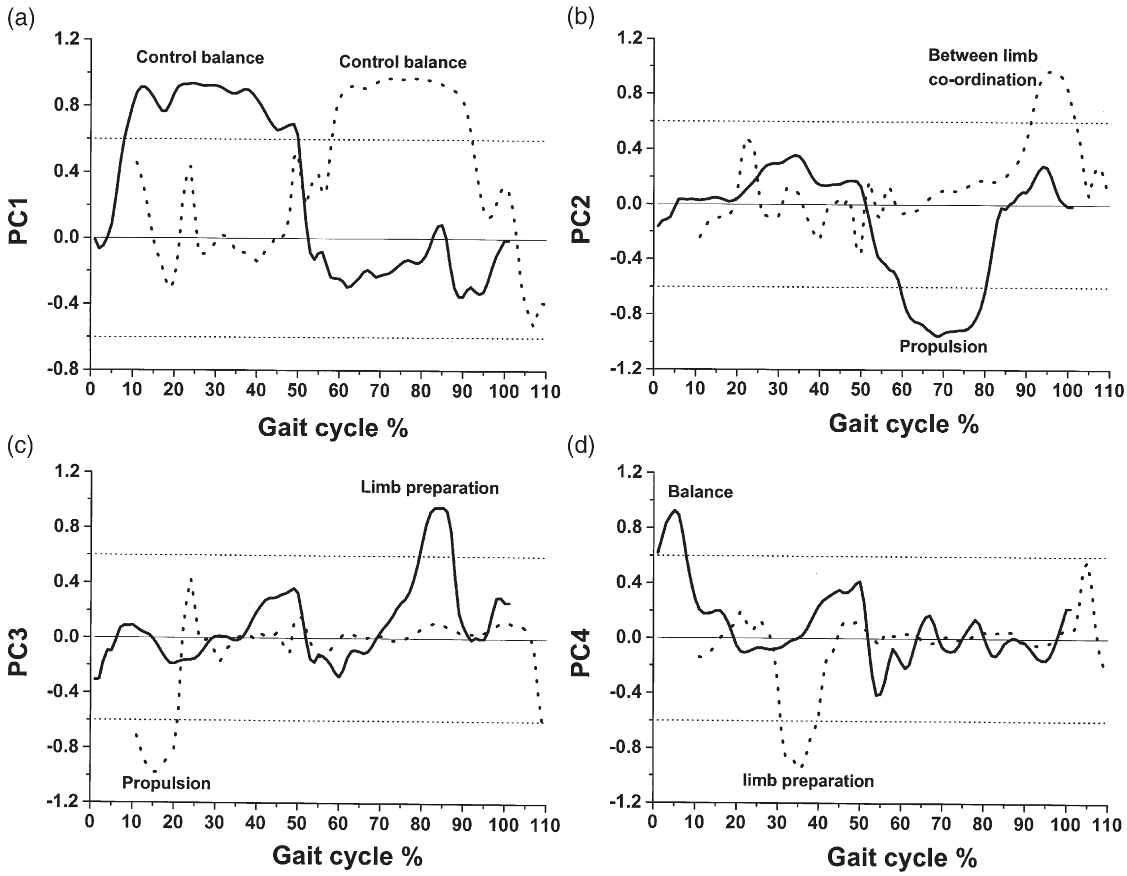

Fig. 3. First four representative curves (PCs) extracted from the hip muscle power curves developed at the right and left lower limbs of 20 able-bodied subjects. The mean muscle power curves calculated at the right (solid line) and left (dashed line) limbs were obtained from two consecutive gait cycles. Gait cycle is presented as a percentage. Muscle power at the left limb is presented from 10% of the gait cycle when the right limb enters the foot-flat position and the left limb enters the swing phase.

the last portion of the swing phase (85–95% of GC). At the left lower limb, although the third PC covered 10% of the variation, the higher factor loading values were given to 60–70% of the GC expressing the role of the hip flexors in the first 10% of the swing phase.

PC4 at the right hip characterised 8% of the remaining extracted variations (Fig. 3d) distributing the higher factor loading during the heel contact and weight acceptance phase (0–10% of GC). The corresponding PC4 for the left side accounted for 9% of the information emphasising the role of hip sagittal muscle action in the last portion of the swing phase (85–95% of GC).

4. Discussion

The main objective of this study was to demonstrate how PCA can be used: (a) to detect the main structure of actions taken by hip extensors and flexors during two consecutive gait cycles of able-bodied subjects, and (b) to determine whether or not symmetrical behaviour exists between right and left hip muscle power activity. To verify these two assumptions, the first four important features of PCA which explain most of the hidden information obtained from hip sagittal muscle power curves were analysed. Our intent was to display only those few curves out of 20 that reflect the important modes of variation present in this generally similar collection of curves. It is important to remember that the PCA displayed in the various figures is one subset of the original curves themselves. No attempt was made to combine information from these curves in order to obtain derived functions not initially present since PCA seeks a few underlying dimensions among the observed original data [23] with little loss of information. One important advantage of PCA is that each PC is orthogonal to all the other PCs. This means that each PC presents completely new information.

4.1. Main features of hip sagittal muscle power curves

The two first representative curves accounted for the largest (and an almost equal proportion) of the observed variables' variance at the right (40%) and left (38%) hips in the sagittal plane. In both of these PCs, the higher factor loading values were quite similarly distributed throughout two-thirds of the mid-stance period (10–40% of GC). Winter [33] used the term "dynamic balance" to explain the action taken by muscles at the hip level during mid-stance. He and his colleagues further suggested that the hip sagittal muscles are the major source of controlling the head, arms and trunk and the centre of mass movement [34]. Based on these observations, we concluded that the first primary and common task for both limbs at the hip level should be explained as the hip flexors and extensors supporting the upper body by assisting in the control of the knee joint during mid-stance [35]. Supporting the body weight transfer during forward progression could be considered as the first appropriate functional task for both right and left hip sagittal muscle power flexors and extensors during natural walking. Our result further supported the idea that the control function is not performed solely by the muscles in the frontal plane, and that the hip muscles in the sagittal plane also contribute to balance control during the stance phase [1,24].

For the right hip, PC2 extracted 18% of the variation from the remaining variability. The negative and significant factor loading values in this component were spread throughout the pull-off and early swing phases (H3S, 55–80% of GC). During this period, the hip flexors at the right limb are responsible for propelling the body weight forward in the plane of progression by pulling the leg up and forward [6] while the muscles are contracting concentrically. For the left hip, PC2 demonstrated 13% of the information hidden in the muscle power curve, while the higher factor loading was distributed throughout the double support phase (40–50% of GC). These results highlighted the role of the hip flexors to transfer the body weight from one limb to the other side. According to this observation, the second representative curve for the right and left hips can be considered as propeller and limb co-ordinator respectively.

Davis and Vaughan [16] interpreted the negative factor loading where muscles work as an inhibitor rather than facilitator. However, according to Ramsay and Silverman [36], PCA of harmonic continuous data is essentially a functional version of a set of regression coefficients. Therefore, negative values over a region mean that sample curves display a positive amount of the type of variation around the mean curve. This will tend to cause negative principal component scores, but what is important is how much the harmonics deviate from 0 rather than their sign.

PC3 for the right limb accounted for 12% of the remaining variations and was orthogonal to all previously extracted PCs. This PC describes the action of the hip extensors (H4S) during the last part of the swing phase (85–95% of GC) [37] where the muscles facilitate the limb entering a new gait cycle. However, the third PC for the left hip covered 10% of the variation, explaining the role of the hip flexors in accelerating the forward motion of the thigh and leg prior to and shortly after the toe-off and early swing phase (H3S) [6]. Therefore, limb preparation could be an appropriate name for the third representative curve for the PC3 for the right limb and propulsion for the left.

PC4 at the right hip characterised 8% of the remaining extracted variations with the high factor loading spread during the heel contact and weight acceptance phase (0–10% of GC). During this phase, the hip muscle power (H1S) is due to an extensor moment which pulls the trunk over the hip [1,38] and contributes to forward progression [6,1]. The corresponding representative curve (PC4) at the left side accounted for 9% of the information, emphasising the role of the hip (H4S) in the last portion of swing phase (85–95% of GC) where the hip extensors acted to prepare the limb to enter the new gait cycle. With respect to these results, the fourth representative curve could be used to characterise the balance provided by the right hip, and limb preparation for the left hip.

Our results are in agreement with those of Winter and Eng [6] characterising hip extensor/flexor activity during the stance phase into three main functional tasks, namely balance, support and propulsion. However, some differences were observed. In our study, support was identified as the main task of the hip for both limbs. Propulsion and limb preparation were the next two common and important contributions of the hip in the gait of both lower limbs, but with a different ordering. Furthermore, in this study, two new tasks were identified for the hip sagittal muscle power curves for both hips, namely balance and co-ordination.

4.2. Functional discrepancy between lower limb tasks

Gait symmetry is assumed when no statistical differences are noted between the parameters of the right and left limbs [2,38]. Using this working assumption, the peak power data were analysed. The results show that the hip behaves symmetrically during able-bodied gait except at pull-off (H3S). The hip flexors of the right limb pulled the leg forward significantly more than the left hip, i.e. by 23%. However, these results do not provide enough information to interpret this difference as an asymmetrical behaviour of muscle activity at the hip, since the comparison was made between two instants of muscle power curves. For this reason, it might be difficult to explain the functional tasks of the lower limbs. PCA as a curve structure detection method is able to solve these problems by providing information which explains the main functional behaviour of the data and might also be used to express the possible existence of a functional discrepancy between the lower limbs. In this study the first four tasks of the right hip were ordered differently from those determined for the left hip, particularly for the second, third and fourth tasks. This result might explain in part the idea of functional gait asymmetry at the hip sagittal muscles.

4.3. Generalisation

The PCA method provides specific information on the population sampled. It is not known if the results obtained from one population can be safely applied to a completely different population. Consequently, the possibility of extracting the same first four PCs from another population should be considered carefully. However, we would expect to see four similar PCs in a similarly homogeneous population as ours.

5. Conclusion

Using principal component analysis, it was possible to demonstrate the contribution and importance of hip sagittal muscle power in four independent sub-tasks, namely control balance, propulsion, between limb coordination and limb preparation, in each stride in able-bodied gait. Discrepancy in task ordering for hip muscle power activity between the right and left sides suggests functional gait asymmetry in able-bodied subjects. The importance of the swing phase was also highlighted, indicating the need to study this portion of the gait cycle in future experiments.

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