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Sagittal plane kinematic analysis of the six-minute walk test: a classification of hemiplegic gait

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Aim. **The aim of this study was to propose a kinematic classification of gait according to six minute walk test performance.**

Methods. **Thirty-four hemiplegic subjects were enrolled. Six-minute walk test (SMWT), gait analysis and Walking Handicap Scale score (WHS) were measured. A k-means cluster analysis was used to classify the sample into three sub-groups which were homogeneous in spatio-temporal parameters, kinematic variables, and which reflected three meaningful levels of walking competency.**

Results. **Three clusters were identified: low-functioning walkers (Cluster 1) walked for 88-172 m; intermediate-functioning walkers (Cluster 2) walked for 180-302 m and high-functioning walkers (Cluster 3) were able to cover 349-430 m. The authors found homogeneous gait profiles in these subgroups. Between-group differences on kinematic data and WHS scores were also underlined.**

Conclusion. **Cluster analysis was able to identify consistent gait characteristics of spatio-temporal, walking endurance and sagittal plane kinematic profiles in hemiplegic subjects and is useful for categorizing the levels of walking competency in these subjects.**

Key words: Hemiplegia - Cluster analysis - Gait, classification.

Following a stroke, more than 80% of survivors are not able to walk independently, although after six months up to 85% can walk unaided.[1] In rehabilitation one of the main goals is to improve walking function. The hemiplegic gait is characterized by a decrease of self-selected speed and changes of gait profile both in magnitude of range of motion and kinematic and kinetic patterns in shape and directions of curves.[2-6] The purpose of classifying gait patterns is to facilitate communication between clinicians and to promote the development of standard clinical pathways for each subgroup.

Previous gait classification studies were based on spatio-temporal, kinematic and kinetic variables and electromyographic (EMG) patterns.[2, 5-8] Olney and Richards studied spatiotemporal variables, kinematic, kinetic and EMG characteristics in three groups of hemiplegic subjects according to gait speed.[3, 7] De Quervain described four kinematic and EMG patterns on the sagittal plane of the knee and the ankle during stance.[2] Mulroy and Kinsella have identified, in recent studies, subgroups of walking patterns based on selected input parameters using quantitative methods for classification construction.[6, 8] Mulroy pointed to the fact that stratification by stride characteristics alone pro-

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TABLE I.—*Subjects characteristics (N.=34).*

	Mean ±SD (min-max)
Age (year)	55.66±14.80 (24-73)
Time since stroke (year)	4.3±4.4 (1-17)
Gender	23M/11F
Hemiplegia's etiology	29 CVA (18 ischemic, 5 hemorrhagic), 5 miscellaneous
Paretic side	18 right/16 left
Mobility aid	20 none/14 cane

duced groups of patients with similar speeds but with widely variable kinematic and EMG patterns. She went on to describe a non-hierarchical cluster analysis of four subgroups of gait patterns based on spatiotemporal and sagittal kinematic parameters of walking.[6] Kinsella has identified three subgroups of chronic stroke survivors with equinus deformity of the foot with homogenous levels of function based on spatiotemporal parameters and joint kinematic and kinetic measures.[8] Gait speed appears to be a critical variable in the classification of hemiplegic gait:[2-4, 6, 7] compared to clinical outcome measures gait speed bears a stronger relationship to the severity of motor impairment. The authors chose to measure gait speed with a long-distance test (six minute walk test) that is a more reliable outcome measure also in low-functioning ambulators with velocity <0.5 m/s.[9, 10] The distance walked in six-minute can reflect levels of walking competency and community ambulation.[11-13]

So the aims of this study were: to classify a sample of chronic hemiplegic subjects in their level of walking performance; to identify different kinematic profiles and ambulation classes in the sub-groups defined.

Materials and methods

Subjects

Thirty-four subjects with chronic hemiplegia were enrolled in this study. The sample was a retrospective sample of convenience based on subjects who were referred to the Motion Analysis Laboratory (MAL) of San Giorgio Hospital located in Ferrara (Italy) for a routine treatment-planning process. Subjects characteristics are summarized in Table I. The inclusion criteria were: hemiplegia at least twelve month before the enrollment; ability to walk unaided for at least six minute at self-selected speed; absence of musculoskeletal disorders, orthopaedic surgery, botulinum injections or phenol nerve block in the hemiplegic lower limb in the five months before the evaluation. All subjects gave informed consent.

Procedures

The walking endurance was measured with the six-minute walk test. This procedure was first used in subjects with cardiopulmonary problems and it was recently introduced to assess the walking endurance and competency in hemiplegic subjects.[10, 11] Subjects were instructed “to walk as far as possible in six minutes, you can slow down and rest if necessary but at the end of the six minutes you should aim to not have been able to walk any further in the time period”.[14] Subjects walked up and down a 20 m walkway without encouragement. They were told how long they had walked for after three minutes and at the last minute. Gait analysis was performed on a 10 m walkway with the subjects walking with or without aid devices (orthosis, cane) according to their ability at a self-selected speed. In order to characterize the community ambulation classes, we used the Walking Handicap Scale (WHS) described by Perry, which is a self-reported measure of community ambulation. It identified six functional categories, the ability to get to appointments, visit friends, go shopping, go to church, and undertake recreational activities; with 4 levels of attainment from “unable” to “independent”.[15] Three-dimensional kinematic of the lower limbs and spatio-temporal parameters were captured using the VICON 460 motion analysis (Oxford Metrics, Oxford, UK) during gait with six cameras (Mcam 50, 100Hz). Fourteen reflective markers were taped onto the skin, overlying the bony landmarks of the pelvis, thigh, tibial shank and foot using methods described by Davis protocol (1991). Three trials were collected for each subject. A Polygon Authoring Tool 2.4 software provided by VICON, allowed the acquisition of kinematic data and spatio-temporal parameters of the gait cycle for every subjects.

Classification construction

The authors used the six-minute walk test to categorize chronic hemiplegic subjects into sub-groups with similar levels of walking performance. They analyzed a set of gait parameters in the sagittal plane kinematic to identify the most frequent deviations described in hemiplegic gait.[3, 16] The authors have incorporated four anatomical levels (pelvis, hip, knee and ankle): maximum ankle plantarflexion in loading response (named A1), maximum ankle dorsiflexion in stance phase (named A2), maximum ankle plantarflexion in pre-swing phase (named A3), maximum knee flexion at loading response (named K1), maximum knee extension in stance phase (named K2), maximum knee flexion in swing phase (named K3), maximum hip flexion in stance phase (named H1), maximum hip extension in stance phase (named H2), maximum hip flexion in swing phase (named H3), maximum pelvic anteversion (named P1). The total sagittal plane range of motion of the ankle, knee, hip and pelvis were measured. Gait speed, cadence, single support double support, stride length were also reported. We used a quantitative statistical construction technique to identify relative homogeneity in groups based on the input variables selected. The data was analyzed using k-means cluster analysis with a preselected number of clusters. A cluster is a collection of data objects that are similar to one another within the same cluster and is dissimilar to the objects in other clusters. If the number of clusters chosen is too small, different clinical profiles may be grouped together, on the other hand if we set a number of groups that is too large, the classification system becomes cumbersome.[17] The quality of a cluster may be represented by its diameter, which is the maximum distance between any two objects in the cluster. To test the power of clusters and to identify outliers, we accepted data with Euclidean distance ratio <1.7.* The distance between final cluster centers is a measure of between-cluster differences.

We chose a three-group classification according to gait speed. This yielded a clinically meaningful functional ambulation classification: low-functioning walkers (<0.4 m/s), intermediate-functioning walkers (0.4 to 0.8 m/s), and high-functioning walkers (>0.8 m/s)

Statistical analysis

K-means, a partitioning method of cluster analysis was used to identify three homogeneous subgroups based on selected variables. Mann-Whitney test was used to test for significance between cluster group differences. Pearson's correlation coefficient was used to test the association between gait speed measured during gait analysis and SMWT. A p-value of 0.05 was set as the criterion for statistical significance. Statistical analysis was performed with SPSS 13.0 package.

*Sample Euclidean distance to final centers (mean)/each case Euclidean distance to final center <1.7

Results

Cluster analysis

From this sample the authors excluded one case with a high Euclidean distance from the center (ratio >1.7): they considered it too far from its cluster for the selected variables (named as outlier). The final classification had thirty-three subjects set into three clusters for walking endurance, spatio-temporal and kinematic variables. The distances between final cluster centers were 123.3 m (Cluster 1 and 2), 160.2 m (Cluster 2 and 3), 281.6 m (Cluster 1 and 3). In Cluster 1 (low-functioning walkers) there were subjects who walked for 88-172 m (mean 118±28.8SD), in Cluster 2 (intermediate-functioning walkers) subjects walked 180-302 m (mean 237±32.6 SD). Cluster 3 (high-functioning walkers) was based on cases who covered 349-430 m (mean 393±25.2 SD). Results were reported in Tables II,III with their between-group significance.

Cluster 1: low-functioning walkers

Nine subjects belonged to this cluster. Reduced dorsiflexion (5.0°) in stance phase was observed on ankle kinematics as well as decreased plantarflexion at push-off (-5.2°). This sub-group showed a stiff-knee pattern with reduced flexion both in stance (1.0°) and swing phases (13.7°). Hip motion reflected a slight flexion reduction in stance (20.5°) and a lack of extension in stance phase (2.4°). Pelvic anteversion was increased (18.3°).

Cluster 2 intermediate-functioning walkers

Thirteen subjects were classified as intermediate-functioning walkers. Ankle motion profile was defined by a slight plantarflexion reduction in stance phase (-3.8°), followed by normal dorsiflexion (10.6°) and reduced plantarflexion during push-off (-1.5°). Knee joint had a normal flexion on loading response (10.4°) with a slight hyperextension in stance phase (-5.2°).

TABLE II.—*Cluster sagittal kinematic profiles (with between groups significance).*

	Variable	C1	C2	C3	Sig. C1-C2	Sig. C1-C3	Sig. C2-C3
Ankle	A1	-11.2 (32.1)	-3.8 (30.3)	-12.6 (39.5)	0.006	NS	P<0.0001
	A2	5.0 (27.3)	10.6 (19,8)	8.1 (26.1)	P<0.0001	NS	P<0.005
	A3	-5.2 (30.1)	-1.5 (43.8)	-8.5 (42.3)	NS	NS	P<0.0001
	ROM	17.7 (20.5)	14.5 (29.5)	17.8 (38.4)	NS	NS	NS
Knee	K1	1.0 (35.9)	10.4 (39.7)	11.2 (36.5)	0.002	0.04	NS
	K2	-7.1 (57.2)	-5.2 (36.8)	-11.0 (31.3)	0.04	NS	0.001
	K3	13.7 (22.2)	25.4 (37.5)	39.0 (36.7)	P<0.0001	P<0.0001	0.001
	ROM	20.6 (50.5)	31.1 (45.2)	45.3 (49.9)	0.008	P<0.0001	P<0.0001
Hip	H1	20.5 (15.5)	24.1 (36.0)	29.9 (31.7)	0.009	P<0.0001	0.01
	H2	2.4 (33.9)	3.1 (49.7)	-9.2 (46.6)	NS	P<0.0001	P<0.0001
	H3	24.0 (17.6)	28.1 (37.9)	36.4 (51.6)	0.003	P<0.0001	0.006
	ROM	13.1 (40.6)	26.1 (36.8)	43.9 (51.4)	0.02	P<0.0001	P<0.0001
Pelvis	P1	18.3 (11.1)	18.9 (30.3)	20.5 (28.3)	NS	NS	NS
	ROM	12.1 (13.4)	10.8 (17.7)	10.1 (20.0)	NS	NS	NS

A1: max ankle plantarflexion in loading response; A2: max ankle dorsiflexion in stance; A3: max ankle plantarflexion in pre-swing; K1: max knee flexion in loading response; K2: max knee extension in stance; K3: max knee flexion in swing; H1: max hip flexion in stance; H2: max hip extension in stance; H3: max hip flexion in stance; P1: max pelvic antiversion. Data are median and range values.

TABLE III.—*Spatio-temporal parameters and community ambulation score (with between groups significance).*

	C1	C2	C3	Sig. C1-C2	Sig. C1-C3	Sig. C2-C3
Speed (gait analysis) (m/s)	0.28±0.11	0.47±0.15	0.83±0.14	P<0.0001	P<0.0001	P<0.0001
Cadence (step/min)	59.0±10.70	76.5±11.9	93.0±9.00	P<0.0001	P<0.0001	P<0.0001
Single support (s)	0.42±0.11	0.42±0.07	0.39±0,05	NS	NS	NS
Double support (s)	0.92±0.23	0.58±0.18	0.37±0.10	P<0.0001	P<0.0001	P<0.0001
Stride lenght (m)	0.57±0.19	0.73±0.16	1.07±0.12	P=0.001	P<0.0001	P<0.0001
Speed (SMWT) (m/s)	0.32±0.08	0.65±0.09	1.09±0.07	P<0.0001	P<0.0001	P<0.0001
WHS scores	4 (3)	5 (3)	6 (1)	NS	P=0.01	P=0.02

Spatiotemporal parameters data are mean±standard deviation values, WHS scores are median and range values.

During swing phase, knee flexion was limited (25.4°). Hip kinematic pattern was defined by normal flexion both in stance (24.1°) and swing phase (28.1°) and a lack of extension in mid stance (3.1°). Pelvic anteversion was increased (18,9°).

Cluster 3: high-functioning walkers

Eleven subjects fell in this class. They were characterized by a nearly normal ankle gait profile with slight limitation in plantarflexion at push-off (-8.5°). The knee joint had good flexion on loading response (11.2°) with a moderate hyperextension in mid stance (-11.0°). Knee flexion during swing phase was also limited in this subgroup (39.0°). Hip kinematic profile was normal. Pelvic anteversion was increased (20.5°).

Spatiotemporal parameters

Gait speed, cadence, stride length and single support time were reduced in all sub-groups while double support time was increased. Our results suggested a linear association between gait speed during gait analysis and 6MWT (r=0.86; P<0.0001).

Discussion

Mobility difficulties result in significant disability associated with hemiplegia, and only 50% of hemiplegic subjects are community ambulators.[11] The authors have classified hemiplegic gait into sub-groups according to gait speed covered in the six-minute walk test, which is a simple evaluation of endurance

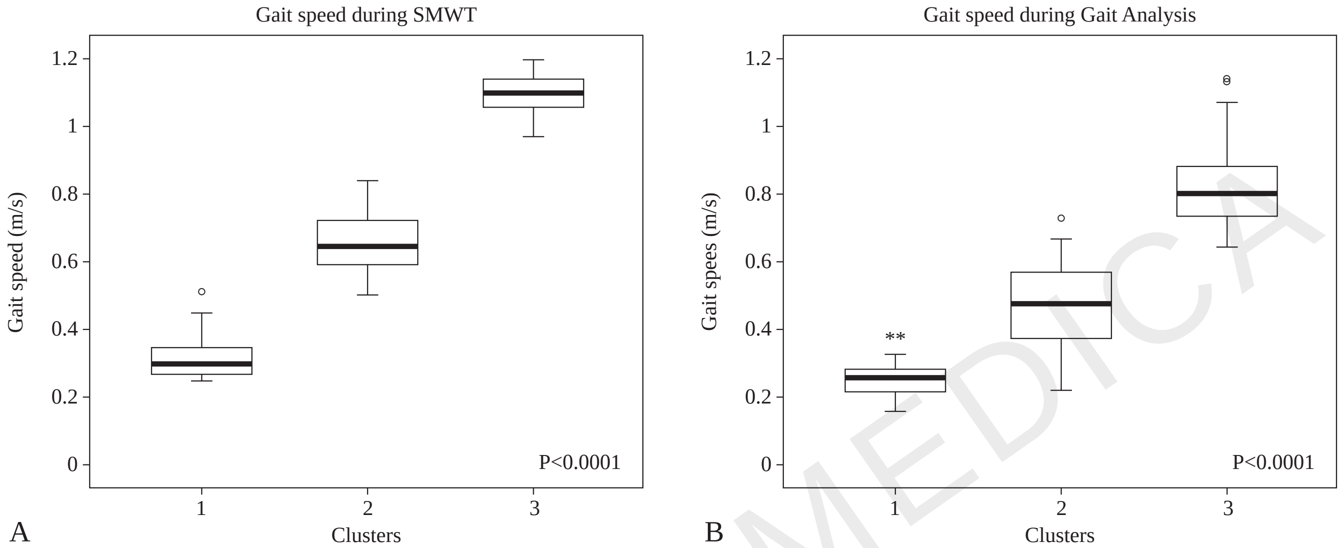

Figure 1.—Gait speed during Gait Analysis and during six-minute walk test (SMWT).

and walking ability. Short-distance walking speed and timed walking distance have been shown to be equivalent measures in clinical trials on hemiplegic subjects who walk at >0.5 m/s. These results show a strong correlation between gait speed measured in the gait lab with gait analysis and the 6 minute walk test even though intermediate and high-functioning walkers (Cluster 2 and 3) had greater gait speeds during the six minute walking test (Figure 1). The ability to increase gait speed in the six minute test compared to self-selected walking speed within the gait laboratory can be seen as a powerful measure to quantify the participation of these subjects in community. Self-selected walking speed within the laboratory setting may be influenced by the constrained environment and instrumentation. As pointed out by Dean *et al.* gait speed over a short distance tends to overestimate locomotor capacity in low-functioning ambulators since these subjects were not able to maintain their comfortable walking speed for longer distances.[10]

Median WHS scores allowed to chategorize the subjects into three groups of self-reported community ambulation levels described by Perry, *i.e.* most-limited community walkers (Cluster 1), least-limited community walkers (Cluster 2) and community walkers (Cluster 3).[15] The authors did not find any differences in WHS scores between low and intermediate functioning walkers. Although they found gait speed to be the most efficient variable in predicting ambulation classification, these findings highlight the difficulty to determine the community ambulation status with gait speed alone, particularly in subjects with severe gait impairment. Community ambulation is a challenging locomotor activity that requires multiple concurrent abilities including walking, cognitive and motor tasks, maintenance of a trajectory and negotiation of unpredictable grounds.

Classification of gait is necessary in rehabilitation to define categories of subjects with similar gait deviations. These can help in diagnosis, and also to delineate the efficacy of treatments. In this study we propose a classification of chronic hemiplegic subjects into different gait profiles based on their level of walking competency. Gait classifications should be constructed around clinically meaningful categories. Qualitative methods, where classification is based on the experience of clinicians, have its clinical relevance, but these interpretations may be subjective. Cluster analysis is a statistical technique that provides a quantitative classification system by separating individuals into discrete groups based on selected parameters.[17] The advantage of a quantitative method is that it leads to a systematic approach. It is then useful for identifying groups or clusters that cannot be easily categorized by visual inspection. One limitation of cluster analysis is that the process may uncover groups that have no clinical relevance and that needs further

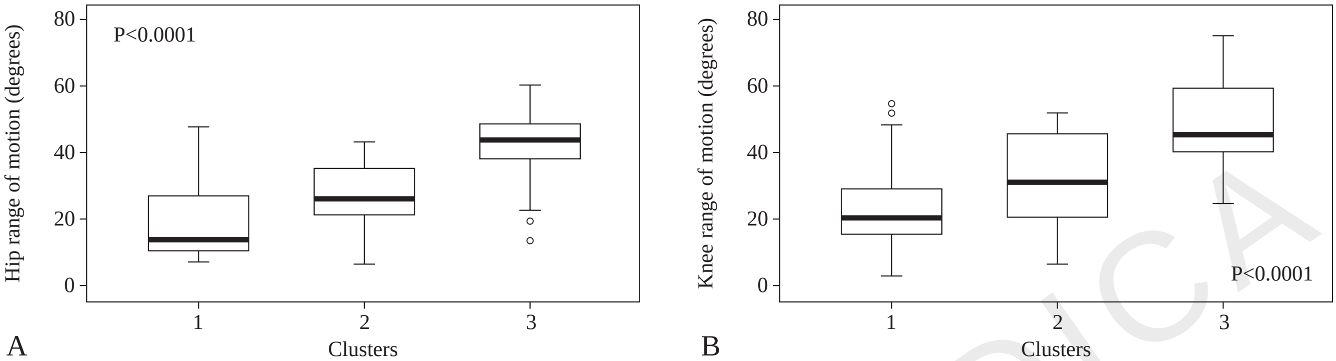

Figure 2.—A) Distribution of hip range of movement in the clusters; B) distribution of knee range of movement in the clusters.

analysis to clearly define between-group differences. For gait classifications with the cluster analysis method, the investigator needs to choose the gait variables for the statistical analysis, to determine the clinical relevance of group allocation. As k-means cluster analysis requires that the number of final groups in the classification is predetermined, a clear rationale should be in place to ensure the validity of this method. For variables, we chose the distance covered in the six-minute walk test, spatio-temporal parameters, essential kinematic sagittal plane values for typical deviations in hemiplegic gait,[3, 16] the range of motion of four anatomical levels and WHS score. The authors did not use coronal and transverse plane variables for our analysis. The clusters identified by this method appeared to be clinically meaningful.[15]

Low-functioning walkers (Cluster 1) were independent in at least one moderate community activity (*i.e.* appointments, restaurants) and needed assistance in low-challenge activities (*i.e.* church, neighborhood, visiting friends). They walked for very short distances in the six-minute walk test (88-172 m) and all spatio-temporal parameters were markedly reduced in this group (Table II). This group was similar to Group 4 (extended) reported by Mulroy and the "extension thrust pattern" described by De Quervain [2, 6] which was characterized by very slow speed and knee extension during the whole of stance phase and decreased ankle dorsiflexion during swing phase. Hip kinematics showed severe limitation of both flexion and extension. Two cases were similar to Mulroy's Group 3 (flexed) which showed increased knee flexion during stance phase and increased ankle dorsiflexion.[6] Hip range of motion was severely limited in this group, as was knee range of movement compared to community walkers ($P<0.001$). Intermediate-functioning walkers (Cluster 2) covered a fair distance in six-minutes (180-302 m) with a decrease in spatio-temporal parameters. They performed moderate community activities without assistance, such as walking to a local store or going to an uncrowded shopping centers. The limited community of walkers was similar to Group 2 (moderate/slight extended) described by Mulroy [6] who achieved intermediate speed with slight knee hyperextension during mid stance and normal ankle dorsiflexion in terminal stance. High-functioning walkers (Cluster 3) were independent at home and in moderate community activities, such as walking on uneven surfaces and to crowded shopping centers. Subjects in this cluster covered a long distance in six minutes (349-430 m). The ankle motion was similar to normal gait with slightly reduced plantarflexion at push-off, according to Olney and Richards's observation of normal ankle pattern in hemiplegic subjects walking at high speed.[3] Hip motion profile was also normal: all subjects had good hip flexion in stance and swing phases and only two cases had reduced hip extension in mid stance. Compared to the less-functional clusters, high-functioning walkers had increased knee flexion in swing phase, and greater knee and hip range of motions. Compared to higher functioning groups, low-functioning walkers (Cluster 1) had severe gait deviations in the sagittal plane, with abnormal hip, knee and ankle motions; the most affected being the hip.[4, 7]

One-way ANOVA was used to test significance between-group differences, to discriminate different kinematic and spatiotemporal profiles. The kinematic parameters that determined between-group differences were hip flexion range in stance and swing phase, hip extension in terminal stance and knee flexion in swing phase. The authors found differences between groups in both hip and knee range of motion, while ankle range of motion was reduced in all clusters without significant differences (Figures 2A,B). According to previous studies, spatiotemporal parameters correlate with walking ability, except for single support time.[18] To summarize between-group differences, in this study the authors have identified the hip as the main determinant of walking endurance. In their studies, Olney and De Quervain reported the same relationship between the hip and gait speed.[4, 7] Kerrigan also showed reduced hip extension to be common in elderly subjects and that it is strongly correlated with falls risk.[19] Inadequate knee flexion in swing was the other kinematic deviation that influenced walking competency. This gait pattern, called the stiff-knee gait, has been associated with prolonged activity of rectus femoris, reduced hip flexion, and reduced ankle plantarflexion at push-off.[20] The authors have shown that knee extension in stance phase is not correlated with walking endurance, as we had previously observed in clinical tests. Another element that supports this is the single support profile, which was not significantly different across clusters. Although gait deviations in the sagittal plane have been well-established, a limitation of this study is that kinematic data were recorded only in this plane.[3, 4] The authors also did not analyze kinetic profiles. Ankle powers may have helped them define the role of plantarflexors during stance phase.[21] This study population had somewhat heterogeneous etiology for hemiplegia. Twenty-nine subjects were stroke survivors and four had other causes hemiplegia.

The identification of three clusters according to walking performance measured with six-minute walking test and the finding of hip and knee impairment as the leading factor of walking performance, may help clinicians in defining an appropriate rehabilitation program. An exercise plan focusing on strengthening and stretching of proximal components may be more effective to increase walking performance in a chronic hemiplegic population

Conclusions

Cluster analysis can successfully identify gait patterns according to spatio-temporal parameters, walking endurance and sagittal plane kinematic profile and may be useful to classify hemiplegic subjects into different levels of walking performance. The distance covered in six-minute walk test was sensitive enough to reflect functional changes in hemiplegic gait.

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