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Evaluation of the bilateral function in para-athletes with spastic hemiplegia: a model-based clustering approach

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Abstract

Objective: Spastic hemiplegia is one of the most common forms of cerebral palsy, in which one side of the body is affected to a greater extent than the other one. Hemiplegia severity (i.e. moderate vs mild forms) is currently used in some Para sports for classification purposes. This study evaluates the sensitivity of several tests of stability (e.g. one-legged stance test), dynamic balance (side-step test), coordination (rapid heel-toe placements), range of movement (backward stepping lunge), and lower limb power (the triple hop distance and the isometric peak force of the knee extensors) to discriminate between the impaired and unimpaired lower extremities' function in para-athletes with spastic hemiplegia.

Methods: A sample of 87 international para-athletes with cerebral palsy took part in the study, and their bilateral performance was measured for the abovementioned tests. The tests' sensitivity to discriminate between impaired vs unimpaired legs was assessed using Boruta's method.

Results: The triple hop distance, the magnitude of the mean velocity in the one-legged stance test and the time to perform the rapid heel-toe placement test are the most sensitive variables when performing random forest classifiers. In addition, the study confirms two optimal clusters by Gaussian finite mixture models to represent the athletes' performance.

Conclusion: Reference scores for the clusters are provided, demonstrating that coordination, balance, and power of the lower limbs are relevant variables for classifying para-athletes with spastic hemiplegia.

Keywords: Paralympic; Para sport; disability; brain impairment; cerebral palsy; classification

Practical Implications

- Bilateral measurements of the coordination (rapid heel-toe placement), balance (centre of pressure accelerations), and lower limbs power (triple hop for distance) could be used to discriminate between impaired and unimpaired lower limbs in para-athletes with different degrees of spastic hemiplegia.
- Cluster analysis with these measurements produced two different groups comprising para-athletes with a similar type of impairment (i.e. unilateral spasticity or hemiplegia).
- This study provides reference scores that may help decision-making in Paralympic classification, improving current methods to assess para-athletes with unilateral spasticity or hemiplegia.
- The reported assessment methods can be used as the basis for developing a new classification system for those para-footballers with spastic hemiplegia currently competing in FT7 and FT8 sport classes.
- Pending replication of the findings with para-athletes with a higher degree of spasticity, these findings may help other Para sports such as para-athletics, para-badminton, para-cycling, para-swimming, para-taekwondo or para-table tennis in applying of scientific methods to classify para-athletes with spastic hemiplegia.

1. Introduction

Hypertonia is one of the 10 eligible impairments in Paralympic sports (i.e. Para sports), which is associated with underlying health conditions such as cerebral palsy, traumatic brain injury or stroke (i.e. brain impairments). Athletes with hypertonia have an increase in muscle tension—including spasticity—and a reduced ability to stretch muscles affected by damage to the central nervous system.[1] Additionally, hypertonia is considered the most common form of cerebral palsy, composing 85–90% of the cases; one-third of them are unilateral and two-thirds are bilateral. Specifically, the unilateral spasticity profile is characterized by an asymmetrical impairment of body movements and muscle tone, i.e. one side is affected to a greater extent than the other side. This asymmetry leads into abnormal motor patterns affecting individuals' general coordination to perform activities of daily living and also sport skills, such as dynamic balance, ability to change direction or jumping capability.

To achieve an equitable and fair competition in Para sports, para-athletes are classified or grouped into sport classes according to how much their impairment affects the outcome of the competition.[2] Therefore, the aim of this classification process is to promote participation by minimising the impact that the athlete's impairment has on the competition outcome.[2] However, the severity of spasticity is mainly assessed with the Ashworth or ASAS scales. Although these scales have shown good values of inter-rater reliability,[3, 4] they are tools that base the evaluation on the testers´ ability. Sometimes, this decision-making is not objective or is mainly based on the spasticity scores obtained during the athlete's assessment on a bench (i.e., their physical assessment). In addition, there is a lack of standardization for the testing positions across different para-sports when using these scales, which compromises the reliability of the classification process. For this reason, Tweedy et al.[5] emphasized the need to develop procedures to measure the impairment based on scientific evidence that has the following attributes: reliability, precision, parsimony, training resistance, and a ratio scale.

In the last three decades, para-athletes that are non-wheelchair users with unilateral spasticity have been usually classified into sport classes giving a special relevance to their impairment severity. For example, moderate/mild forms of hemiplegia have been categorized as T37/T38 runners or F37/F38 throwers in para-athletics, or FT7/FT8 players in cerebral palsy (CP) football.[3] They represent 52% of the runners and standing throwers with brain impairments in para-athletics, as well as 60% of the total population practising CP football worldwide. In addition, the severity of spasticity is also used in other Para sports, such as para-badminton, para-cycling, para-swimming, para-taekwondo, or para-table tennis. However, team para-sports, such as CP football, are very physically demanding because of the complex number of factors that determine their performance.[4] Passing, running, jumping, dribbling, and changing direction are some of the most common abilities required to succeed in football, and these abilities will be affected to a greater or lesser extent depending on the impairment severity in the para-athletes' lower limbs.[3] Although there have been several attempts to improve the classification systems that assess para-athletes' lower limb function through different quantifiable tests, the results from these studies have showed some limitations concerning classification use: small sample sizes, involving para-athletes with different levels of functioning,[6] or grouping participants with different eligible impairments such as hypertonia, ataxia, and athetosis within the same group.[7]

Recently, a new approach like the model-based hierarchical clustering has been applied in the field of Paralympic sport classification,[8] and it could potentially be a comprehensive strategy for classification to increase the objectivity of this complex process. To our knowledge, this is the first study exploring the performance asymmetries in para-athletes with unilateral spasticity that considers different dimensions of the impaired muscle tone and its application for the decision-making in Paralympic classification. The aims of this study were: 1) evaluating tests' sensitivities—with regard to stability, dynamic balance, coordination, range of movement, and power—to discriminate between the impaired and unimpaired lower limb function in para-athletes with unilateral spasticity and 2) clustering these para-athletes according to their functionality/performance level.

2. Material and methods

Participants: Eighty-seven international male para-athletes (Age = 25.8 ± 6.7 yr; Body mass = 69.2 ± 8.6 kg; Height = 1.75 ± 0.7 m) with CP or related neurological conditions that provoke spastic hemiplegia participated in the study. All participants were classified as Level I according to the Gross Motor Function Classification Scale [9], that is: able to walk independently, able to climb curbs and stairs without physical assistance or a railing, and able to perform gross motor skills such as running and jumping but speed, balance and coordination are limited. All of them had a profile of moderate (FT7 = 74) or mild (FT8 = 13) spastic hemiplegia and 89.9% of them had taken part in at least one worldwide competition. All the participants were selected to be part of the international CP football squads, representing a total of 10 countries from Europe (n = 5), North America (n = 2) and South America (n = 3). All participants provided written informed consent after a detailed written and oral explanation of the potential risks and benefits resulting from their participation in the study. They had the option to voluntarily withdraw from the study at any time.

Measures: Six tests to measure different abilities were conducted: range of movement with the backward stepping lunge (BSL);[7] lower limb strength—peak of force—by an isometric measurement of the knee extensors (PF);[10] coordination with rapid heel-toe placements (RHT);[3] dynamic balance with the side-step test (SS);[11] a combination of impaired power intra-limb coordination and stability,[12] measured with the triple-hop for distance field test (TH);[13] and static balance with the one-leg stance (OLS) test, measured as magnitude of mean velocity (VMM).[14] All the instruments required for testing, outcomes, and protocols are described in Supplementary Material 1.

Procedures: Data were collected in an intercontinental tournament to qualify for the CP Football World Championships. Information about the protocols was sent in advance to the teams. To minimise learning effects, two trials were conducted per leg, using the best score for the subsequent statistical analyses. Para-athletes were divided into several stations to perform the tests, so 2–3 participants were always in each station; one individual performed the test at a time while the others were resting. Every test was administrated by the same researcher for consistency and both legs were tested starting by unimpaired.

Data and Statistical Analyses: The recorded variables were categorised as impaired ($Test^{i}_{t}$) or unimpaired ($Test^{U}_{t}$) leg, considering the impaired side to be the leg with some degree of spasticity. The difference of performance between legs was measured as follows: $Test_{t} = Test^{U}_{t} - Test^{i}_{t}$. All the variables and their units are also described in Supplementary Material 1.

Test sensitivities were compared using the Boruta method,[15] a variable selection wrapper capable of working with any classifier that returns the importance of each variable for the classification. The method performs a top-down search for relevant variables by comparing each variable's importance with the importance of shuffled copies of the original variables—which are called shadow features—and progressively eliminates irrelevant variables in order to stabilise the accuracy of the classifier. A random forest (RF) classifier, which is an ensemble of decision trees used for classification and regression tasks,[16] was used as the base classifier for the Boruta method. The goal of this analysis was to order the tests according to their importance or sensitivity in determining the para-athlete's impaired side. Classification models were based on standard binary recursive partitioning of conditional inference trees.[17]

The participants were clustered according to the differences in their performance measured in each test. A clustering method based on Gaussian finite mixture models was used to represent the para-athletes' performance as a Gaussian finite mixture with different covariance structures and mixture components.[18] This method performs a preliminary analysis of the data in order to determine the optimal number of clusters and the best modelling. It allows the presence of overlapping clusters, producing a probabilistic representation that quantifies the uncertainty of athletes to belong to components of the models' mixture.[19] Once the probabilistic model's fitting is completed, the obtained clusters can be visualized in a two-dimensional space, which contributes to getting a better description and interpretability of the results.[20] The Bayesian information criterion (BIC) was used to fit the clustering mixture of models according to the differing parameterizations and the number of components or clusters. The BIC is the standard criterion for selecting the order of the mixture based on penalised forms of the log-likelihood.[21] Practical significance between cluster scores was assessed by calculating Cohen's effect size according to the values suggested by Rhea[22] for highly trained athletes: above 1.0, between 1.0 and 0.50, between 0.50 and 0.25, and lower than 0.25 were considered as large, moderate, small, and trivial, respectively.

All data analyses were performed using the R Statistical Software version 3.4.2 (R Core Team).

Results

Prior to statistical analyses with all the tests included in the study, a RF classifier was used to identify the most sensitive variable obtained from the force platform in the OLS test. According to this test, the VMM was the most sensitive variable and it was used for the subsequent statistical analyses.

Prior to the identification of the most effective test for determining the impaired side, the Wilcoxon two-sided paired test demonstrated the existence of significant statistical differences in performance between the impaired and the unimpaired lower extremities ($P < .01$). Tests' importance was obtained with the Boruta method ($P = .01$, RF runs = 1000) showing the Triple Hop was the most relevant test, while the VMM of the OLS and the RHT were also very sensitive. The PF and the BSL tests were reported to be irrelevant to determine the level of difference between the impaired and unimpaired body sides (See Supplementary Material 2).

Based on these results, a conditional inference classifier was used in order to build a classification model for predicting the impaired side using the results of the most sensitive tests. Figure 1 shows the decision tree obtained, which contains two internal nodes: TH test—the root node, the most important variable—and the VMM from the OLS test. The global classification accuracy achieved with this decision tree was 0.95; only 4 para-athletes were misclassified.

INSERT FIGURE 1 NEAR HERE

The fitting process of the clustering model and the best model is estimated by the highest BIC value (see Supplementary Material 3). From the 14 available parameterizations for the models, the VVE model (ellipsoidal, equal orientation) was selected as the best model according to the Fraley and Raftery[23] statistical criterion (log-likelihood = −177.5, BIC = −106.9). This model identifies the presence of two major clusters of athletes with spastic hemiplegia. These clusters can be projected onto a suitable two-dimensional reduction subspace, which allows visualization of the clustering structure and the geometric characteristics induced by the estimated Gaussian finite mixture models fitted.

Figure 2 shows the projection of the two clusters obtained by the VVE model on the two-dimensional subspace. These two projected dimensions explain 41.5% and 15.8% of the total variance in the data. The points represent 83 para-athletes with spastic hemiplegia and the shape of these points depicts their classification into two major clusters with 42 and 41 para-athletes, respectively.

INSERT FIGURE 2 NEAR HERE

The clustering results were validated by comparing the classification accuracy obtained using the two original sport classes, FT7 and FT8, with respect to the two classes proposed by our clustering method. For this aim, two RF classifiers were trained and tested using the same data via stratified 10-fold cross-validation. The performance of the classifier using the two classes proposed by the clustering method (mean accuracy = 0.85, kappa = 0.95) was significantly higher than the original binary classification model (mean accuracy = 0.70, kappa = 0.77) for the same set of parameters. Both results were compared statistically using a paired *t*-test ($P < .01$). Table 1 shows the mean values and standard deviations of performance obtained for each cluster. For example, an athlete with between-legs differences of VMM = 0.1 mm/s, TH = 1.4 m/m, RHT = 7.2 s, BSL = 1.6 m, SS = 10.2 m/m, and FP = 410.5 N would be classified in Cluster 1. Accordingly, the 83 para-athletes (FT7 = 71 and FT8 = 12) included in the final model are classified as follows: Cluster 1 (FT7 = 40 and FT8 = 3) and Cluster 2 (FT7 = 31 and FT8 = 9). Considering Cluster 1 for those para-athletes with a higher level of impairment (i.e. FT7), this model implies that 40.96% of the para-athletes do not align with their current sport class.

INSERT TABLE 1 NEAR HERE

Discussion

All Para sports are required to have evidence-based classification systems that promote fair participation by minimising the impact that the athlete's impairment has on the competition outcome.[2] This study evaluates the sensitivity of different performance tests executed by para-athletes with spastic hemiplegia and explores the relevance of the following dimensions of this eligible impairment in Para sports: static balance, dynamic balance, power, coordination, the range of movement, and isometric strength. The performance ratio between unimpaired vs impaired legs was used to cluster para-athletes according to the most sensitive variables.

The TH and the VMM were the two variables that best discriminated between impaired vs unimpaired legs, being included in the conditional inference tree for predicting the impaired side of para-athletes with spastic hemiplegia. To confirm the previous findings of this specific profile of people with brain impairments,[12] our study showed that TH is a valid and reliable test to assess asymmetries in jump capacity in people with spastic hemiplegia. Probably, TH is the best test for discriminating between impaired and unimpaired leg function, because a high score on this test demands not only strength and power capacity of the lower limbs but also intersegmental coordination and stability. Taking into account that horizontally-directed jumps (hip-thrusts) have been associated with maximum acceleration phases when sprinting,[24] which are also required in CP football[25] as well as fast and frequent changes of direction;[26] our results confirm its appropriateness for classification. Accordingly, TH has been included in the newest classification rulebooks for para-athletics and CP football (i.e. 2018 versions).

Concerning balance ability, it should be noticed that people with spastic forms of brain impairments exhibit upper motor neuron signs, including spasticity, hyperreflexia, and extensor plantar response;[26] these constrain the leg distal movements and affect their ability to keep unilateral balance and perform rapid heel-toe-placements. People with CP and related neurological conditions are also characterized by the performance of gross—rather than fine—and individual movements, besides performing slow and effortful voluntary movements.[27] These movements affect their capacity to keep an upright, weight-bearing position. A previous study involving a group of participants with hemiplegia demonstrated they had greater sway velocities in standing, slower weight transfer times in sitting and standing tests, and slower turning times in a step and quick-turn test.[28] The relevance of the VMM outcomes for balance assessment is confirmed by our sensitivity analyses that indicate that this variable is the most sensitive for the discrimination of balance impairment between legs, instead of other centre of pressure parameters. Therefore, it is plausible to think that this variable may reflect the fine-tune adjustments performed by the participant to keep a stable, upright position and optimize their postural control.

The RHT was used to assess the distal coordination of the lower limbs, and it appeared to be the third most sensitive test to discriminate between legs. People with spastic hemiplegia tend to have impaired movement coordination and reduced between-limb synchronisation of the impaired side,[29] particularly considering the velocity-dependent resistance of the muscle to passive stretch caused by spasticity.[30] The time constraints to perform the RHT test exacerbate the abovementioned plantar extension response because of the co-contraction[31] of the spastic muscles, which affects the accuracy of the toe contacts performed and the capability of performing the required heel contacts. From a para-sport specific domain, only one study[7] measured impaired coordination using a tapping test founding that none of the three coordination measurements significantly correlated with the sprint performance in runners with brain impairments and controls. In contrast, RHT requires a form of intra-limb coordination, in which the participants must contact different spots during the test, which demands considerable coordination.

There are three dimensions of the impairment that exhibited lower (i.e., SS) or no sensitivity at all (i.e., PF and BSL) to discriminate between legs. The SS test was recently included in para-athletics to assess activity limitation in runners with hypertonia, athetosis, or ataxia; however, it does not seem to be a suitable test for this purpose since the spasticity in proximal joints (i.e. adductors/abductors) does not have a high impact performing wide steps. Additionally, the low execution speed might not increase the spasticity either in para-athletes with moderate-to-mild spastic hemiplegia. Regarding the PF, unlike other studies that used isometric laboratory protocols to assess the more impaired side in runners with brain injury [6], the difficulty isolating leg extension movement during our field protocol might bias the results. Finally, the BSL did not properly discriminate between impaired and unimpaired legs either. These results are consistent with Connick et al.[7] who assessed ROM in runners with brain injury and obtained no significant differences when compared with controls.

The cluster analyses confirmed that the two clusters find clear distinction among the performance levels of para-athletes with spastic hemiplegia according to the tests applied. This clustering method has been recently used in wheelchair racers according to their muscle strength and sprint performance,[8] showing that 19% of the participants (n = 32) were allocated to clusters that did not align with their current sport classification. Considering the number of participants in the current study, the proportion of mismatches is similar (n = 83, 40.96%). As a practical application, clustering methods based on ability test provide an objective and quantitative information that may be helpful in the making decision process for the current classification model.

To the best of the authors' knowledge, this is the best study clustering para-athletes with hypertonia, specifically with moderate (i.e. FT7 sport class) or mild (i.e. FT8 sport class) forms of spastic hemiplegia. Our study provides reference scores to cluster para-athletes with unilateral spasticity, but the dispersion of the participants in Cluster 1 might suggest that the inclusion of athletes with more severe forms of hemiplegia could shape 3 profiles according to the outcomes of the best tests that discriminate between impaired vs unimpaired legs. Therefore, more research is necessary that involves para-athletes with a higher degree of impairment.

The present study has some limitations that should be mentioned. First, the results can only be applied to international level CP football para-athletes with spastic hemiplegia. Second, the measurement of the centre of pressure velocity requires expensive equipment that may not be available in some settings, so new portable and wearable tools are required. Finally, our model did not include an assessment of the spasticity based on a manual test (i.e. Ashworth or ASAS scales) or with an objective tool as an isokinetic dynamometer that could improve the classification decision process.

Conclusions

In conclusion, measurements of the impaired coordination (RHT, but also required in the TH), balance (VMM in the OLS test, but also required in the TH), and lower limb power (TH) are sensitive variables to discriminate between impaired and unimpaired legs in para-athletes with spastic hemiplegia. In addition, the two clusters provide reference scores to shape evidence-based sport classes, and it is suggested that the inclusion of para-athletes with more severe impairments might improve the clustering efficacy. Finally, we suggest that further research is necessary that involves participants with other eligible impairments associated with cerebral palsy or related neurological conditions, such as ataxia or athetosis, in order to identify the variables that best discriminate between different levels of impairment.

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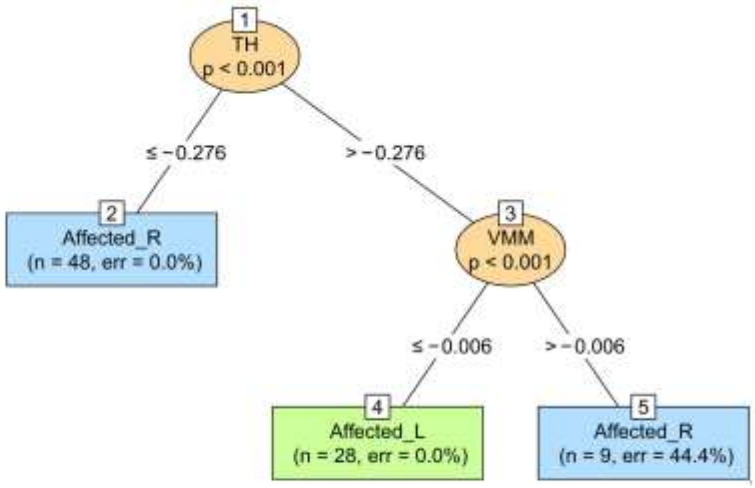

Figure 1 Representation of the conditional inference tree built for predicting the impaired side of para-athletes with spastic hemiplegia. Circular internal nodes show the top-down split of the most discriminating tests of performance. Squared leaf nodes represent the predicted class (impaired body side, left or right), the number of observations in the node (n), and the classification error obtained on the node (err). *TH* triple hop (in m/m), *VMM* magnitude of the mean velocity in the one-leg stance test (in mm/s)

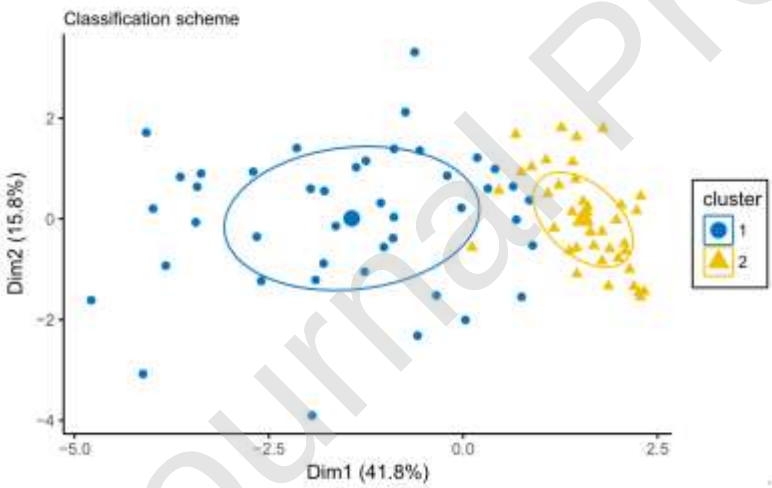

Figure 2 Projection of the participants with hemiplegia, clustered according to the VVE model. Different points' shapes indicate the pertinence of the clusters. Component means are marked as the centres and ellipses with axes are drawn corresponding to their covariance

Table 1 Results obtained with the impaired side (*mean* ± *SD*) in each test for the clusters

	Tests	Cluster #1	Cluster #2	Effect Size	
1	One Leg Stance [VMM] (mm/s)	0.14 ± 0.05	0.06 ± 0.02	2.07	Large
2	Triple Hop for distance (m/m)	1.45 ± 0.76	1.92 ± 0.61	-0.67	Moderate
3	Rapid Heel Toe placement (s)	8.07 ± 1.95	7.04 ± 1.45	0.59	Moderate
4	Backward Stepping Lunge (m)	1.59 ± 0.33	1.72 ± 0.32	-0.40	Small
5	Side-Step (m/m)	10.32 ± 1.79	10.54 ± 1.39	-0.14	Trivial
6	Force-Peak of Knee Extensors (N)	416.54 ± 131.02	408.33 ± 96.90	0.07	Trivial

VMM the magnitude of the mean velocity