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A Cross-sectional Observational Study

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Objectives: The aim of the study were to (1) investigate what physical and physiological parameters are most important for Frame Running capacity, a parasport for individuals with ambulatory difficulties, and (2) determine whether Frame Running capacity can be predicted in athletes with cerebral palsy.
Design: Athletes with cerebral palsy ($N = 62$, Gross Motor Classification System I–V; 2/26/11/21/2) completed a 6-min Frame Running test. Before the 6-min Frame Running test, muscle thickness, passive range of motion (hip, knee, ankle), selective motor control, and spasticity (hip, knee, ankle) were measured in both legs. In total, 54 variables per individual were included. Data were analyzed using correlations, principal component analysis, orthogonal partial least square regression, and variable importance in projection analysis.
Results: The mean 6-min Frame Running test distance was 789 ± 335 m and decreased with motor function severity. The orthogonal partial least square analysis revealed a modest degree of covariance in the variables analyzed and that the variance in the 6-min Frame Running test distance could be predicted with 75% accuracy based on all the variables measured. Variable importance in projection analysis indicated hip and knee extensor spasticity (negative effect), and muscle thickness (positive effect) arose as the most important factors contributing to Frame Running capacity.
Conclusions: These results are an important resource to enable optimization of training regimes to improve Frame Running capacity and contribute to evidence-based and fair classification for this parasport.

What Is Known

- Frame Running is a parasport designed for athletes with moderate-to-severe walking/running difficulties. The physical characteristics related to Frame Running capacity, and their hierarchical importance has never been investigated.

What Is New

- We used a multivariate analysis approach that offered a prediction model and an interpretation of the hierarchical importance of the investigated factors. Spasticity in the hip and knee extensors contributed most to the prediction analysis, followed by muscle thickness, especially in the vastus muscles. These data enable optimization of training regimes to improve Frame Running capacity and contribute to evidence-based and fair classification for this parasport.

Key Words: Cerebral Palsy, Parasport, Frame Running, RaceRunning, Performance

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The data sets used during the current study are available from the corresponding author on reasonable request.
Ferdinand von Walden and Rodrigo Fernandez-Gonzalo have equal contribution to this study.
EH and FvW did the conceptualization, methodology, data curation, data analysis, funding acquisition, and writing—original draft preparation. CL did the methodology, data analysis, and writing—original draft preparation. LBS did the data curation and writing—original draft preparation. JP did the data curation, methodology, and writing—reviewing and editing. JN and AP did the data curation and writing—reviewing and editing. GS did the data analysis, software, visualization, and writing—reviewing and editing. EP did the methodology, data analysis, and writing—reviewing and editing. RF-G did the conceptualization, methodology, data curation, data analysis, visualization, and writing—original draft preparation. All authors have read and agreed to the published version of the manuscript.
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Frame Running (FR, previously known as RaceRunning) is a parasport designed for athletes with moderate-to-severe walking and/or running difficulties. For these individuals, it is one of the few options that enable physical activity at moderate to high intensity.[1–3] Most FR athletes have a diagnosis of cerebral palsy (CP),[4] a group of movement and posture disorders caused by a lesion on the developing brain. Depending on the timing, location, and extent of brain damage, the severity of activity limitations will differ.[5] In addition to movement and postural disturbances, CP is often accompanied by impairments in perception, sensation, cognition, communication, and behavior, and/or epilepsy.[5] For some individuals, these accompanying disturbances interfere as much or even more than the motor impairments. However, in CP, movement, posture, balance, and coordination are always affected.[5] The type of neurological disorder is categorized into spastic (bilateral or unilateral), dyskinetic (dystonia, choreaathetosis), and ataxic.[5] The five-level Gross Motor Classification System (GMFCS) is used to describe function in individuals with CP. [6] Regardless of the degree of motor and/or other impairments, individuals with CP may have a limited ability to take part in physical activity, and are at risk of poor health, due to the condition itself, secondary complications, and sedentary behavior.[7] Frame Running has emerged as an option that not only increases physical activity but also has great potential of embracing the holistic approach of the F-words framework (functioning, family, fitness, fun, friends, and future),[8] a concept grounded in the World Health Organization's International Classification of Functioning, Disability and Health (the ICF) for improved participation and quality of life. Even for individuals at GMFCS I who can walk independently but have limitations in speed, balance, and coordination, FR can be a safe and fun way to engage in physical activity and be part of a sports community. How different types of impairments influence FR capacity is, however, not fully elucidated.

Data on typically developing athletes clearly underline that to excel in sports with diverging requirement profiles, different physical characteristics are needed. For example, the typical sprint runners have large muscles able to produce high-power, high-frequency strides relying on mainly anaerobic metabolism.[9] Intuitively, for medium- and long-distance runners, muscle mass ought to be less of a priority and muscle endurance and cardiorespiratory capacity of greater importance. However, several studies have demonstrated that increased strength[10] improves running economy, which in turn has positive implications for capacity. For individuals with CP the picture is likely even more complex. Although the brain damage in CP is nonprogressive, the clinical presentation typically changes over time. Secondary musculoskeletal pathophysiology develops with advancing age,[11] with, for example, muscles becoming weaker, thinner, and underdeveloped because of altered growth.[11,12] In addition, decreased joint range of motion starts early in life, often developing into fixed contractures.[13] Information on what factors contribute to FR capacity in athletes with CP is sparse. To our knowledge, only two studies have addressed this research question and exclusively in relation to sprint speed. Their results showed that spasticity, selective motor control, muscle function, knee range of motion (i.e., contractures >20 degrees),[14] and trunk control[15] affect FR sprint speed. However, the design of these studies does not allow for an interpretation of the hierarchical importance of these factors. In addition, other phenotypic aspects with potential importance for FR capacity, such as muscle mass or subcutaneous fat thickness,[16] have never been considered.

To further explore which physiological variables favor FR capacity is relevant for several reasons. First, it enables optimization of treatment and training regimes aiming to improve FR capacity. Second, this knowledge can contribute to the development of an evidence-based and fair classification system for FR, which is crucial for the sport to grow as a parasport event. Given this background, we aimed to investigate the influence of physical and physiological parameters on FR capacity. First, we investigated multiple functional and capacity variables in CP individuals in relation to their GMFCS level. Once this was completed, we set our primary research questions as (1) What physical and physiological parameters are most important for FR capacity? and (2) Can FR capacity be predicted, based on physical and physiological parameters? We also performed analyses to determine the hierarchical order of the variables contributing to FR capacity in individuals with CP.

MATERIAL AND METHODS

Study Design and Procedures

This is a cross-sectional study on FR capacity in individuals with CP (Supplemental Digital Content STROBE Checklist). Frame Running capacity was assessed with the 6-min Frame Running test (6-MFRT).[2] Heart rate (HR, Garmin Edge 25) was monitored throughout the test and the rating of perceived exertion (RPE, Borg 6–20 scale) was collected before and immediately after the 6-MFRT. On the same day and before the FR capacity test, a physical examination was performed by experienced physiotherapists, exercise physiologists, and physicians. For a given variable, the same evaluator assessed all the subjects. All evaluators had several years of experience using the test used to assess the specific outcome.

Participants

Individuals with CP were recruited during the international event "RaceRunning Camp and Cup" in Copenhagen in 2018 and 2019 ($n = 46$) and from FR-clubs in Sweden ($n = 16$). Inclusion criteria were a diagnosis of CP and age between 7–45 yrs. Exclusion criteria were orthopedic surgery and/or injections of botulinum toxin within 3 mos before the study. All participants were informed and signed a formal consent before entering the trials. Participants could discontinue their participation at any time and withdraw their consent. For individuals younger than 18 yrs or with problems to understand the information provided (i.e., intellectual disability), consent from parents or guardians was obtained. The study was approved by the Swedish Ethical Review Board (Ethical permit; DNR: 2016/1139-31/2 with addendums; DNRs 2016/1675-32, 2017/2237-32, and 2020-04170).

Six-Minute Frame Running Test

The 6-MFRT test measures the maximal distance covered by the individual with the frame runner during 6 mins around a running track. The participants were verbally encouraged throughout the test and a companion was allowed to run/walk next to the athlete for encouragement and safety. Distance was measured to the nearest meter using a trundle wheel. Heart rate and speed were recorded throughout the test. Before and immediately after the

6-MFRT, participants were asked to rate their perceived exertion using the RPE Borg scale.[17]

Passive Range of Motion

Passive range of motion (pROM) of hip (flexion, extension, abduction), knee (flexion, extension, hamstrings angle), and ankle (dorsiflexion with extended knee) was measured with a goniometer in both legs.[18]

Selective Motor Control

The selective motor control (SMC) scale of active ankle dorsiflexion by Boyd and Graham[19] was used to measure both feet. This is an ordinal scale (0–4) where 0 is no active movement and 4 is an isolated active dorsiflexion of the foot throughout the available range of motion.

Spasticity

The Modified Ashworth Scale[20] was used to assess muscle spasticity of muscles around hip, knee, and ankle in both legs. This is an ordinal scale (0, 1, 1+ 2, 3, 4) measuring resistance to passive elongation of a muscle at rest.

Skeletal Muscle and Subcutaneous Fat Thickness

Skeletal muscle and subcutaneous fat thickness (in millimeters) of thigh (vastus lateralis and vastus intermedius together) and calf (medial gastrocnemius muscle) was assessed in both legs with ultrasound (Siemens Acuson s2000; Siemens, Erlangen, Germany, or Synergy MSK Ultrasound; Arthrex, Sweden) as previously described.[1,12]

Additional Information Collected

The participants' gross motor function was classified using the Expanded and Revised Gross Motor Function Classification System (GMFCS E&R)[6] and the Functional Mobility Scale (FMS).[21] The subtype of CP was classified based on dominant neurological feature: spastic (bilateral or unilateral), dyskinetic, or ataxic CP. Additional personal information was collected: age, sex, height, weight, FR experience, competitive CPISRA (Cerebral Palsy International Sports and Recreating Association) class (i.e., RR1, RR2, RR3, where RR1 is represented by FR athletes with severe impact on their motor function and RR3 represents those with milder functional impairments), medical history (surgery or spasticity-reducing interventions), pain, and perceived difference between sides (i.e., more- and less-affected side). Decisions about which side was judged to be more or less affected were based on muscle size, self-perceived difference, and SMC. In five cases, side difference was hard to determine and was decided after revising spasticity and pROM data.

Data Analysis

The analysis included 54 variables per individual. Because there were only two participants in GMFCS I, they were grouped together with participants with GMFCS II (i.e., group GMFCS I–II). Similarly, the two participants in GMFCS V were included in the group of individuals with GMFCS IV (i.e., group GMFCS IV–V). To analyze potential differences in FR capacity and physical parameters depending on GMFCS-levels, a one-way analysis of variance was used. To analyze whether there was a difference between capacity and physical parameters for more- or less-affected legs in relation to the GMFCS-levels, a two-way analysis of variance was used. To compensate for multiple post hoc comparisons the Tukey multiple comparisons test was used. Spearman rank correlation was performed using *corrplot* R package to investigate the associations between the investigated physical parameters and distance covered in the 6-MFRT. For this analysis, a ρ value of 0.00–0.10 was regarded as negligible, 0.10–0.39 as weak, 0.40–0.69 as moderate, 0.70–0.89 as strong, and 0.90–1.00 as very strong correlation. Significance level was set at $P < 0.05$. In addition, data were analyzed and plotted in R using *FactoMineR*, *factorextra*, and *ropls* packages to perform principal component analysis (PCA) and orthogonal partial least square (OPLS) regression, followed by variable importance in projection (VIP) analysis. The dimensionality-reduction method PCA was used to visualize the underlying correlations between 6-MFRT distance, GMFCS, and all the other variables measured. Orthogonal partial least square regression is a multivariate projection method to extract the relationships between a set of predictor variables to one or more responses. Orthogonal partial least square was computed in the current experiments to determine the degree of predictability of the 6-MFRT distance based on the rest of variables that were measured. Then, the contribution of each variable to the OPLS projection was determined with VIP analysis.

RESULTS

Participants

Sixty-two participants (mean age 22 ± 9, 32 males/30 females) with CP (GMFCS I–V) took part in the study. There were no significant differences between the GMFCS groups regarding height, weight, sex, or age (Table 1). Frame Running experience ranged from 1 mo to 26 yrs of experience.

Tests and Physical Examinations

Distance covered during the 6-MFRT was 789 ± 335 m, for the total group, and decreased with higher GMFCS-level (Fig. 1A). The GMFCS I–II group ran significantly further than GMFCS III ($P = 0.0164$) and IV–V ($P < 0.0001$). Participants in the GMFCS IV–V group reached a lower maximum speed than those in the GMFCS I–II ($P < 0.0001$) and III ($P = 0.0319$) groups (Fig. 1B). Peak and average HR were 176 ± 23 and 158 ± 29 beats per minute, respectively, and RPE immediately after the 6-MFRT was 16.5 ± 2.3, with no differences across GMFCS levels (Figs. 1C–F).

Passive range of motion was in general more limited at higher GMFCS levels (significant main effects of GMFCS level for all pROM variables ($P < 0.0001$ to $P = 0.003$) except for ankle dorsiflexion, which was equally limited in all groups ($P = 0.263$), and knee flexion, which was mostly without deficit in all three groups ($P = 0.135$). There was no significant difference between sides in any pROM variable (Supplemental Table 1, Supplemental Digital Content 1, http://links.lww.com/PHM/B1000).

Selective motor control could not be evaluated in six participants because of logistical problems during the tests performed in the FR clubs in Sweden. The measurements

TABLE 1. Descriptive characteristics of the participants

<table>
<tr><th></th><th>GMFCS I–V (All) (N = 62)</th><th>GMFCS I–II (n = 28)</th><th>GMFCS III (n = 11)</th><th>GMFCS IV–V (n = 23)</th></tr>
<tr><td>Male/female</td><td>32/30</td><td>14/14</td><td>6/5</td><td>12/11</td></tr>
<tr><td>Age, yr</td><td>22 ± 9 (9–45)</td><td>22 ± 10 (9–45)</td><td>22 ± 8 (11–43)</td><td>22 ± 8 (11–35)</td></tr>
<tr><td>Height, cm</td><td>157 ± 13 (123–182)</td><td>159 ± 15 (123–182)</td><td>155 ± 11 (140–168)</td><td>154 ± 12 (123–170)</td></tr>
<tr><td>Weight, kg</td><td>51 ± 16 (23–87)</td><td>54 ± 17 (23–87)</td><td>52 ± 10 (37–67)</td><td>48 ± 16 (23–87)</td></tr>
<tr><td>BMI, kg/m^2</td><td>21 ± 5 (13–34)</td><td>21 ± 5 (15–34)</td><td>21 ± 3 (17–27)</td><td>20 ± 5 (13–34)</td></tr>
<tr><td>Unilat spastic|bilat spastic|dyskinetic|ataxic</td><td>2|36|21|3</td><td>2|16|7|3</td><td>0|7|4|0</td><td>0|13|10|0</td></tr>
<tr><td>FMS 5 m (1|2|3|4|5|6)</td><td>25|5|2|1|25|4</td><td>1|0|0|0|23|4</td><td>3|3|2|1|2|0</td><td>21|2|0|0|0|0</td></tr>
<tr><td>FMS 50 m (1|2|3|4|5|6)</td><td>32|9|0|1|19|1</td><td>4|3|0|1|20|1</td><td>5|6|0|0|0|0</td><td>23|0|0|0|0|0</td></tr>
<tr><td>FMS 500 m (1|2|3|4|5|6)</td><td>39|6|0|2|14|1</td><td>7|4|0|2|14|1</td><td>9||0|0|0|0</td><td>23|0|0|0|0|0</td></tr>
<tr><td>CPISRA class (FR1|FR2|FR3|FR4|missing)</td><td>25|22|11|3|1</td><td>1|14|10|3|0</td><td>4|5|1|0|1</td><td>20|3|0|0|0</td></tr>
<tr><td>FR experience, yr</td><td>5 ± 6 (0–26)</td><td>3 ± 3 (0–10)[a]</td><td>6 ± 5 (0–15)</td><td>9 ± 7 (2–26)</td></tr>
</table>

Values are presented as mean ± SD (min–max) or number of participants per category.
[a] Significantly different than GMFCS IV–V group ($P < 0.001$).

performed in the remaining 56 participants showed that SMC of ankle dorsiflexion was more affected at higher GMFCS levels (main effect of GMFCS level, $P < 0.001$; Supplemental Table 2, Supplemental Digital Content 1, http://links.lww.com/PHM/B1000). Likewise, spasticity was in general more marked at the higher GMFCS levels (significant main effects of GMFCS level, $P < 0.0001$ for all muscle groups) except for foot plantar flexors, where all individuals were affected equally ($P = 0.532$). There was no significant difference between sides regarding SMC or spasticity in any muscle group (Supplemental Tables 2 and 3, Supplemental Digital Content 1, http://links.lww.com/PHM/B1000).

Muscles were thinner in both the thigh and the calf for participants at the higher GMFCS levels (main effect of GMFCS level, $P < 0.0001$). In addition, both muscle groups were thinner in the more-affected leg as compared with the less-affected leg (main effect of side; $P < 0.05$; Figs. 2A, B). There were no differences in thigh subcutaneous fat thickness across groups or legs (Table 2). However, subcutaneous fat thickness in the calf seemed to be higher in the GMFCS III group (main effect of GMFCS level, $P = 0.006$; Table 2).

Correlation Analysis

There were significant moderate correlations between the 6-MFRT distance and all descriptive parameters of motor function classification such as GMFCS-level (Spearman $\rho = -0.64$, $P < 0.001$), competitive class (CPISRA classification) (Spearman $\rho = 0.67$, $P < 0.001$), and functional mobility scale (Spearman ρ for 5 m = 0.65, for 50 m = 0.53, for 500 m = 0.45, $P < 0.001$ for all), but not age ($P = 0.36$) (Supplemental Table 4 [Supplemental Digital Content 2, http://links.lww.com/PHM/C2], Supplemental Fig. 1 [Supplemental Digital Content 3, http://links.lww.com/PHM/C3]). Significant moderate/stronger ($\rho > 0.4$) correlations were also found between 6-MFRT distance and spasticity (in the muscle groups of hip extensors, flexors and adductors, and knee extensors), muscle thickness of thigh and calf, SMC of ankle dorsiflexion, and pROM (hip extension and knee extension; Supplemental Table 4 [Supplemental Digital Content 2, http://links.lww.com/PHM/C2], Supplemental Fig. 1 [Supplemental Digital Content 3, http://links.lww.com/PHM/C3]). There were weak significant correlations between distance in the 6-MFRT and peak and mean HR during the test (peak HR $\rho = 0.39$; $P = 0.002$, mean HR $\rho = 0.37$, $P = 0.003$) (Supplemental Table 4 [Supplemental Digital Content 2, http://links.lww.com/PHM/C2], Supplemental Fig. 1 [Supplemental Digital Content 3, http://links.lww.com/PHM/C3]).

Principal Component Analysis, OPLS Regression Analysis, and VIP Analysis

The PCA revealed a modest degree of covariance in the variables analyzed, with 30% and 11% of the variance captured by the first two principal components (Supplemental Fig. 2, Supplemental Digital Content 4, http://links.lww.com/PHM/C4). This indicated that most of the variables contributed to component 1 or 2, or both. Therefore, all the variables were included in the next analysis, OPLS regression analysis. The OPLS regression analysis indicated that the variance in individual FR capacity (i.e., 6-MFRT distance) could be predicted with a 75% accuracy from the summed effect of all the variables included in the analysis (Fig. 3A). To follow up these results and explore which variables carried more weight in our prediction model (i.e., what variables contributed the most to explain the variance in the 6-MFRT), we performed a VIP analysis, which showed that spasticity in hip extensors and knee extensors, and muscle thickness in vastus (lateralis and intermedius) and gastrocnemius muscles, followed by SMC and pROM of hip extension and knee extension, were the variables that contribute the most to the prediction model (Fig. 3B).

DISCUSSION

This study explored the physical and physiological variables that influence FR capacity, measured with the 6-MFRT. To achieve this goal, we used a multivariate analysis approach that offered a prediction model and a subsequent interpretation of the hierarchical importance of the investigated factors. Spasticity in the hip and knee extensors contributed most to the prediction model, followed by muscle thickness, especially in the vastus muscles. Selective motor control and pROM of the hip

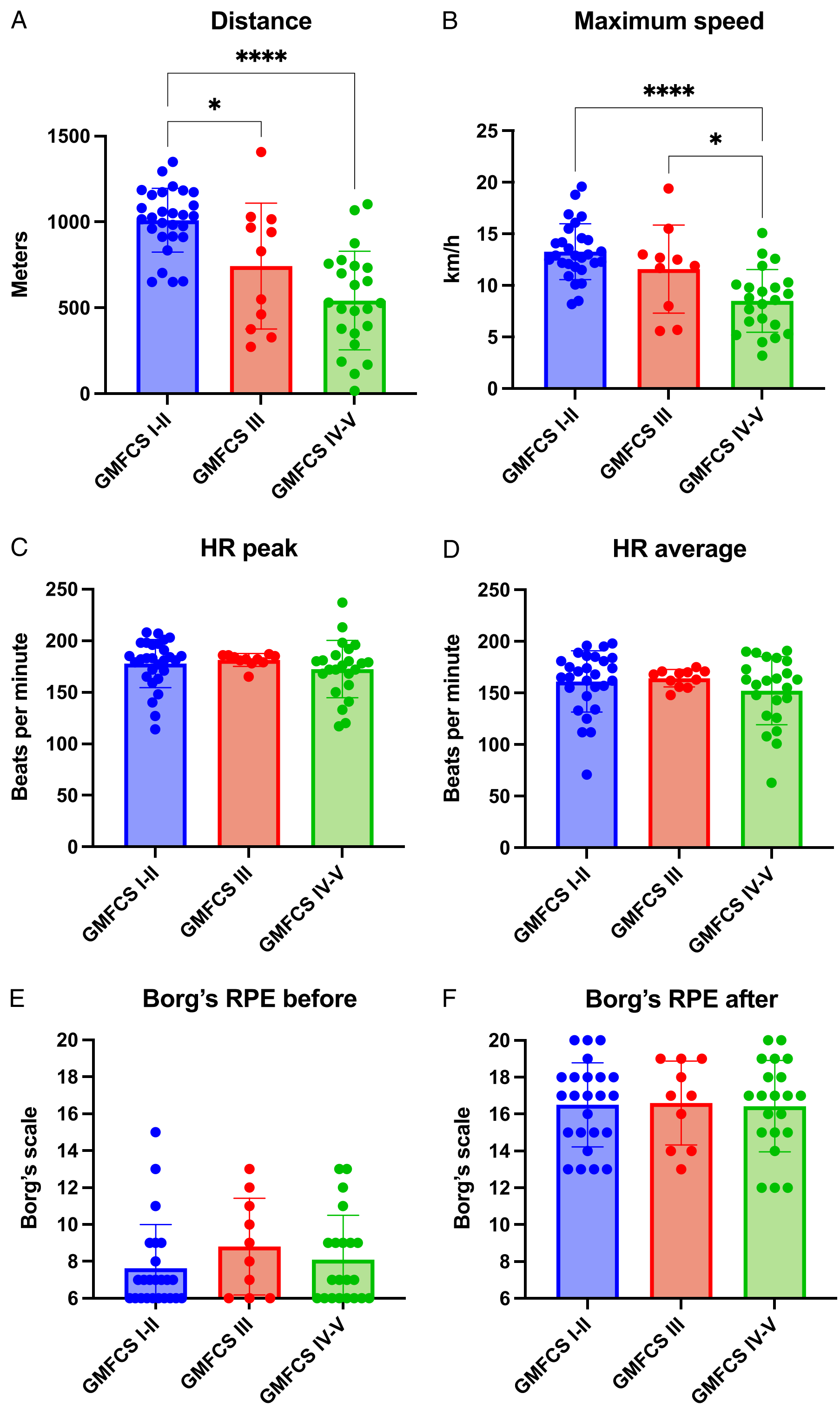

FIGURE 1. A, Distance covered in the 6-MFRT. B, Maximum speed in the 6-MFRT. C, Peak HR during the 6-MFRT. D, Average HR during the 6-MFRT. E, Borg's RPE results before the 6-MFRT. F, Borg's RPE results after the 6-MFRT. Note: *$P < 0.05$, ****$P < 0.001$.

and knee extensors were also among the top-ranked variables in the model. Overall, our prediction analysis based on more than 50 variables was able to predict 6-MFRT capacity (i.e., distance) with 75% accuracy. Furthermore, we observed that a 6-MFRT is a high-intensity and demanding activity, inducing high HR and ratings of perceived exertion in athletes with CP at all GMFCS levels. Overall, the results presented in the current study could be used to optimize training regimes to improve FR capacity and contribute to evidence-based and fair classification for this parasport.

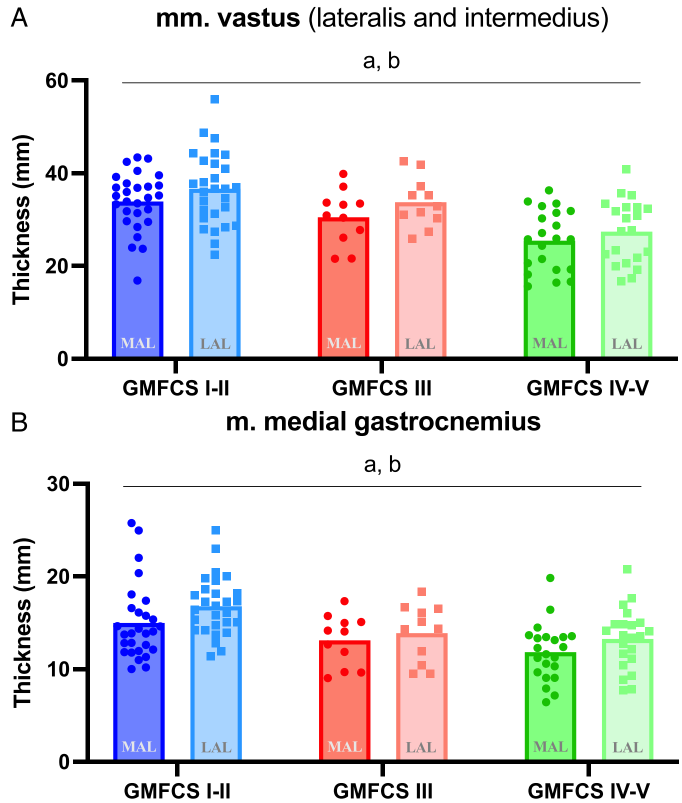

FIGURE 2. Muscle thickness assessed by ultrasound in the mm. vastus (vastus lateralis and vastus intermedius) and m. medial gastrocnemius in the MAL and LAL legs. Note: a; main effect of GMFCS level, $P < 0.0001$, b; main effect of side, $P < 0.05$. LAL, less-affected legs; MAL, more-affected legs.

Spasticity and SMC have already been purported as important factors affecting FR sprint speed in individuals with CP (i.e., 100 and 200 m).[14,15] The relationship between spasticity and gross motor function,[22–24] walking,[22] or running[25] in individuals with CP has been widely discussed but remains inconclusive.[22–25] Indeed, the relationship between these factors is complex.[23] In any case, many investigations conclude that SMC seems to influence capacity[23,24,26] to a greater extent than spasticity and range of motion. Our correlation analysis indicated that SMC was correlated with spasticity. Similar relationships between spasticity and SMC in ankle dorsiflexion have been demonstrated previously.[23] Given these results pointing toward a close interrelation among these variables and the limitations of bilateral correlation analyses, we used new and more advanced methods (i.e., OPLS followed by VIP analysis) to show that spasticity at the hip extensors was the factor that contributed the most to our prediction model and thus 6-MFRT capacity. Selective motor control in ankle dorsiflexion and spasticity at the knee extensors were also among the top variables in our VIP analysis, indicating its importance for FR capacity.

The relationship between muscle size and strength,[27] as well as muscle size and running capacity,[9] is well known in typically developing individuals. This association seems to be weaker in individuals with CP because of what seems to be an altered neural drive, causing muscles affected by CP to be underpowered in relation to their muscle size.[28] Notwithstanding, muscle size in individuals with CP has been found to predict maximum voluntary strength[12] and to have a greater impact on the Gross Motor Function Measure than spasticity (modified Ashworth scale rating).[26,29] Supporting the studies highlighting the importance of muscle size in individuals with CP, our result showed that muscle thickness is an essential factor for FR capacity, with the thigh muscle group emerging as somewhat more important than the calf muscles. It remains to be shown, however, if FR capacity can be improved by resistance training and hence an increased muscle mass. Along this line, and although they did not address the impact on FR capacity, previous studies reported functional improvements after resistance exercise training in individuals with CP.[30] In addition, our research group reported that a 12-wk training period with FR twice a week resulted in hypertrophy of the calf muscle on the more-affected side.[1] All in all, it seems that increased muscle mass could be used to improve FR capacity. This brings important questions to classification routines for

TABLE 2. Subcutaneous fat thickness assessed by ultrasound (in millimeters)

		GMFCS I–II (*n* = 26)	GMFCS III (*n* = 11)	GMFCS IV–V (*n* = 21)
Thigh	MAL	14.0 ± 8.1	16.7 ± 9.7	13.1 ± 7.2
	LAL	13.3 ± 8.6	18.0 ± 10.6	12.4 ± 6.3
Calf[a]	MAL	8.9 ± 4.1	12.7 ± 5.0	9.7 ± 3.3
	LAL	9.0 ± 4.7	12.0 ± 5.1	10.3 ± 3.3

Values are presented as mean ± SD. For thigh, $n = 60$; for calf $n = 61$.
[a] Main effect of GMFCS, $P = 0.006$.

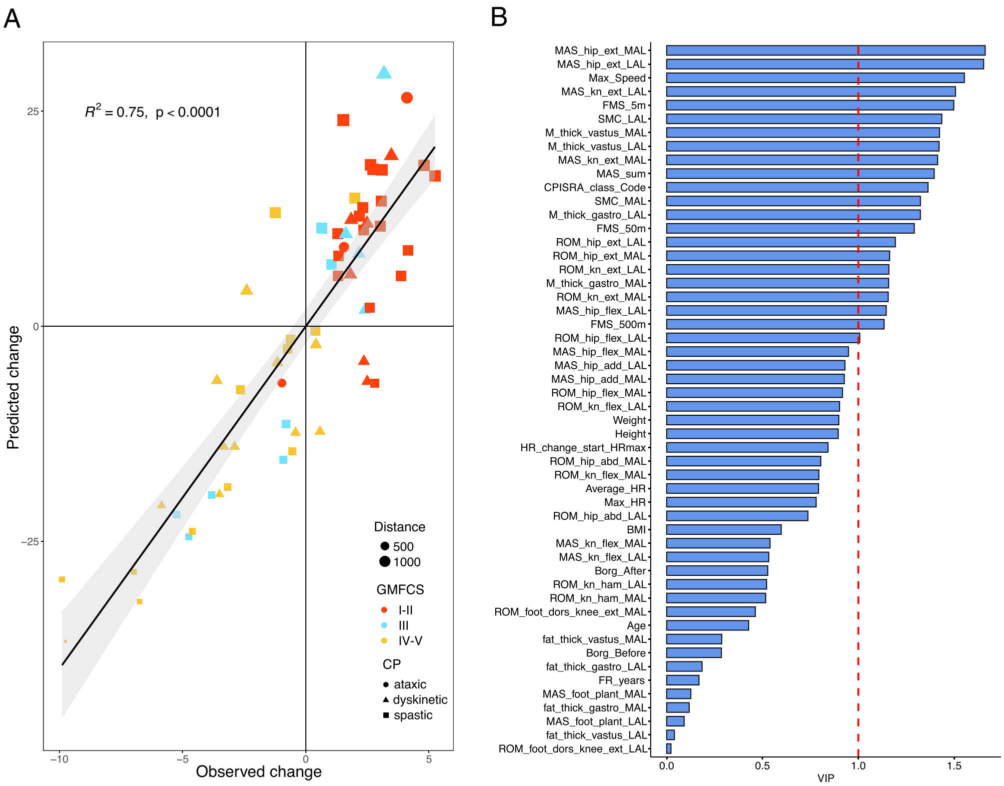

FIGURE 3. Global, exploratory approach to the 6-MFRT capacity (i.e., distance) based in all the variables analyzed (n = 52). A, Scatter plot of predicted and observed 6-MFRT distance using our OPLS regression (R^2 = 0.75, P < 0.001). Gray area represents 95% confident intervals. Each symbol denotes the predicted versus observed distance for one individual. The size of the symbol indicates the distance, while the color represents the group according to the GMFCS level, and the type of symbol describes the type of CP. B, Variable importance in projection showing the hierarchical contribution of each variable to the successful modeling. A value greater than 1 denotes important contribution to the prediction model. abd, abduction; BMI, body mass index; dors, dorsiflexors; ext, extension; fat_thick, subcutaneus fat thickness; flex, flexion; FR_years, years of experience in Frame Running; gastro, gastrocnemius; ham, hamstrings; HR, heart rate; kn, knee; LAL, less-affected leg; M_thick, muscle thickness; MAL, more-affected leg; ROM, range of motion.

FR, and some authors have argued that tests of muscle strength should be excluded from classification protocols[14,15] because of their trainability condition.

In the current study, we chose to use the 6-MFRT as a measure of FR capacity. The 6-MFRT has been validated for individuals with CP with GMFCS III–V.[2] Recently, we showed that this test represents a (near) maximum effort for most individuals with CP and that it can be used as an estimate of cardiorespiratory endurance.[3] In addition, the test has proven useful to evaluate the effects of a 12-wk FR training intervention, showing significant improvements (i.e., 34%) in distance, which were interpreted as an improvement in cardiorespiratory endurance.[1] An important aspect to consider is that all the participants in the study could complete the test, independently of their motor function ability. This would not have been possible had we used tests used by others (e.g., 100 or 200 m) to assess FR capacity,[14,15] as some individuals completed less than 100 m. Therefore, we feel confident that the 6-MFRT is an appropriate instrument to evaluate FR capacity in individuals with CP at all GMFCS levels.

The results presented in this work should be interpreted with some considerations in mind. Most of the variables measured and included in the analysis correspond to lower limb characteristics. Future studies should also include data related to trunk control and upper limb function. Another factor that can impact FR capacity is the technique used to propel the frame runner forward. Thus, motion analysis and measures of running economy, as well as maximal oxygen uptake and anaerobic capacity, would add an extra dimension to FR capacity analysis in individuals with CP. Furthermore, the recruitment of participants for this study was mainly performed at an international FR camp and competition, which could have translated into a more-trained-than-average population with a great interest in FR. Thus, the result of this study may not be generalized to other groups of individuals with CP with low activity levels. In addition, to further validate the prediction model used here, these analyses need to be tested in other populations of CP individuals. Despite these issues, this is one of the largest (N = 62) studies addressing exercise capacity in individuals with CP at all GMFCS levels. In addition, we have added outcomes measures that are novel in this field (e.g., muscle thickness, subcutaneous fat thickness) and that can add important information to FR capacity and general health of individuals with CP. Importantly, the multivariate analysis performed offers a clear interpretation of the hierarchical importance of all the investigated variables, which could prove of great value to develop a fair FR classification system and optimized training strategies for FR athletes.

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REFERENCES

1. Hjalmarsson E, Fernandez-Gonzalo R, Lidbeck C, et al: RaceRunning training improves stamina and promotes skeletal muscle hypertrophy in young individuals with cerebral palsy. *BMC Musculoskelet Disord* 2020;21:193
2. Bolster EA, Dallmeijer AJ, de Wolf GS, et al: Reliability and construct validity of the 6-minute racerunner test in children and youth with cerebral palsy, GMFCS levels III and IV. *Phys Occup Ther Pediatr* 2017;37:210–21
3. Edelman Bos AMM, Hjalmarsson E, Dallmeijer AJ, et al: Physiological response to the 6-minute frame running test in children and adults with cerebral palsy. *Pediatr Phys Ther* 2022;34:529–34
4. Van der Linden ML, Van Schie PEM, Hjalmarsson E, et al: Athlete-perceived impact of frame running on physical fitness, functional mobility and psychosocial outcomes. *J Rehabil Med* 2022;54:jrm00273
5. Rosenbaum P, Paneth N, Leviton A, et al: A report: the definition and classification of cerebral palsy April 2006. *Dev Med Child Neurol Suppl* 2007;109:8–14
6. Palisano RJ, Rosenbaum P, Bartlett D, et al: Content validity of the expanded and revised Gross Motor Function Classification System. *Dev Med Child Neurol* 2008;50:744–50
7. Ryan JM, Allen E, Gormley J, et al: The risk, burden, and management of non-communicable diseases in cerebral palsy: a scoping review. *Dev Med Child Neurol* 2018;60:753–64
8. Rosenbaum P, Gorter JW: The ‘F-words’ in childhood disability: I swear this is how we should think! *Child Care Health Dev* 2012;38:457–63
9. Barbieri D, Zaccagni L, Babić V, et al: Body composition and size in sprint athletes. *J Sports Med Phys Fitness* 2017;57:1142–6
10. Blagrove RC, Howatson G, Hayes PR: Effects of strength training on the physiological determinants of middle- and long-distance running performance: a systematic review. *Sports Med* 2018;48:1117–49
11. Graham HK, Rosenbaum P, Paneth N, et al: Cerebral palsy. *Nat Rev Dis Primers* 2016;2:15082
12. Moreau NG, Simpson KN, Teefey SA, et al: Muscle architecture predicts maximum strength and is related to activity levels in cerebral palsy. *Phys Ther* 2010;90:1619–30
13. Cloodt E, Wagner P, Lauge-Pedersen H, et al: Knee and foot contracture occur earliest in children with cerebral palsy: a longitudinal analysis of 2,693 children. *Acta Orthop* 2020;92:1–9
14. van der Linden ML, Jahed S, Tennant N, et al: The influence of lower limb impairments on RaceRunning performance in athletes with hypertonia, ataxia or athetosis. *Gait Posture* 2018;61:362–7
15. van der Linden ML, Corrigan O, Tennant N, et al: Cluster analysis of impairment measures to inform an evidence-based classification structure in RaceRunning, a new world para athletics event for athletes with hypertonia, ataxia or athetosis. *J Sports Sci* 2020;39(sup1):159–66
16. Lisón JF, García-Herreros S, Ricart B, et al: Ultrasound measurements and physical fitness of elite youth basketball players. *Int J Sports Med* 2023. doi:10.1055/a-1989-9602
17. Borg GA: Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 1982;14:377–81
18. Mutlu A, Livanelioglu A, Gunel MK: Reliability of goniometric measurements in children with spastic cerebral palsy. *Med Sci Monit* 2007;13:Cr323–9
19. Boyd RN, Graham HK: Objective measurement of clinical findings in the use of botulinum toxin type a for the management of children with cerebral palsy. *Eur J Neurol* 1999;6:S23–35
20. Bohannon RW, Smith MB: Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther* 1987;67:206–7
21. Graham HK, Harvey A, Rodda J, et al: The functional mobility scale (FMS). *J Pediatr Orthop* 2004;24:514–20
22. Ross SA, Engsberg JR: Relationships between spasticity, strength, gait, and the GMFM-66 in persons with spastic diplegia cerebral palsy. *Arch Phys Med Rehabil* 2007;88:1114–20
23. Ostensjo S, Carlberg EB, Vollestad NK: Motor impairments in young children with cerebral palsy: relationship to gross motor function and everyday activities. *Dev Med Child Neurol* 2004;46:580–9
24. Noble JJ, Gough M, Shortland AP: Selective motor control and gross motor function in bilateral spastic cerebral palsy. *Dev Med Child Neurol* 2019;61:57–61
25. Bohm H, Wanner P, Rethwilm R, et al: Prevalence and predictors for the ability to run in children and adolescents with cerebral palsy. *Clin Biomech (Bristol, Avon)* 2018;58:103–8
26. Chruscikowski E, Fry NRD, Noble JJ, et al: Selective motor control correlates with gait abnormality in children with cerebral palsy. *Gait Posture* 2017;52:107–9
27. Lieber RL, Fridén J: Functional and clinical significance of skeletal muscle architecture. *Muscle Nerve* 2000;23:1647–66
28. von Walden F, Hjalmarsson E, Reimeringer M, et al: Comparative analysis of power, work and muscle activation during weight-stack and iso-inertial flywheel resistance exercise in young adults with cerebral palsy. *J Rehabil Med* 2020;52:jrm00060
29. Ohata K, Tsuboyama T, Haruta T, et al: Relation between muscle thickness, spasticity, and activity limitations in children and adolescents with cerebral palsy. *Dev Med Child Neurol* 2008;50:152–6
30. Collado-Garrido L, Parás-Bravo P, Calvo-Martín P, et al: Impact of resistance therapy on motor function in children with cerebral palsy: a systematic review and meta-analysis. *Int J Environ Res Public Health* 2019;16:4513