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Classification of the Gait Patterns of Boys With Duchenne Muscular Dystrophy and Their Relationship to Function

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Abstract

Corticosteroids have recently been shown to reduce expected loss of muscle strength in patients with Duchenne muscular dystrophy and extend the time they can walk. We evaluated 43 boys with the condition to determine whether taking corticosteroids is associated with differences in gait pattern, gross motor skills, energy efficiency, and timed motor performance. We used the gait deviation index to quantify the degree of gait pathology and a single measure of gait quality. There were minimal differences in gait pattern, gross motor skills, energy efficiency, or timed motor performance in boys who took corticosteroids compared with those who did not. Clustering by gait deviation index, however, revealed subtle differences between groups in gait patterns, gross motor skills, and energy efficiency. We conclude that, in boys with Duchenne muscular dystrophy, gait pattern deviations are related to function, which can provide further insight into the understanding of disease progression and treatment options to enhance function and maintain ambulation.

Keywords

Duchenne muscular dystrophy; gait; function; energy

Duchenne muscular dystrophy is an X-linked recessive disease of muscle characterized by progressive loss of functional muscle mass, which is replaced with fibrofatty tissue.¹ Historically, boys with Duchenne muscular dystrophy lose the ability to walk between the ages of 8 and 12 years, secondary to progressive muscle weakness coupled with the development of contractures at the hip, knee, and ankle.¹ Recently, corticosteroids have been shown to reduce the expected loss of muscle strength, extend the time these patients can walk and stand, and minimize or eliminate spinal deformity.^{2–4} Yet it is not clear

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Author Contribution

SST, CEB, AB, CMM, and MDS contributed to study concept and design. SST, CEB, AN, and AB contributed to acquisition of data. SST, CEB, AB, CMM, and MDS contributed to analysis and interpretation of data. SST drafted the manuscript. SST, CEB, AB, CMM, and MDS performed critical reviews of the manuscript. SST performed statistical analysis. MDS obtained funding and acted as study supervisor.

Declaration of Conflicting Interests

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whether corticosteroid use just extends ambulatory ability or whether the pattern of functional loss differs between boys who use corticosteroids and those who do not.

Various methodologies have been used to categorize the gait patterns of individuals with neuromuscular disorders. Principal component analysis, clustering techniques, and subjective groupings have been used to classify the gait patterns of children with cerebral palsy and other neurological disorders.⁵⁻⁷ For boys with Duchenne muscular dystrophy, gait patterns are commonly described in terms of differences from normal⁸ or differences in the magnitude of specific kinematic and kinetic indices between boys on corticosteroids and those who are corticosteroid naïve.⁹ Evaluating boys with Duchenne muscular dystrophy by their gait deviations can provide greater insight into the primary deficits and secondary compensations made as a result of muscle weakness. Such information can lead to the development of optimal treatment plans to address specific gait deviations, similar to the use of gait analysis in the treatment of individuals with cerebral palsy.¹⁰

The gait deviation index was developed to quantify the degree of gait pathology relative to normal and to provide a single measure of gait quality.¹¹ Joint rotations are used to define 15 mutually independent gait features that describe each individual's walking pattern. The scaled distance between the 15 gait feature scores for the subject and the average gait feature scores of a control group of typically developing children defines the composite gait deviation index, providing a measure of the magnitude of gait deviation. A gait deviation index value of 100 is normal, and a change of 10 is the value of 1 standard deviation from normal. The lower the gait deviation index score, the greater the magnitude of gait deviation from normal.

For boys with Duchenne muscular dystrophy, disease progression is often marked by a considerable decrease in muscle strength and gross motor skills and increases in timed motor performance and energy cost.¹² To date, differences in gait patterns and their relationship to other markers of disease progression have not been objectively quantified in boys with Duchenne muscular dystrophy. The purpose of this study was 2-fold. First, we sought to characterize gait patterns in boys with Duchenne muscular dystrophy using 2 methods: (1) gait patterns based on corticosteroid use, corticosteroid versus corticosteroid naïve; and (2) use of the 15 kinematic features of the gait deviation index to cluster patterns of deviation. Second, we examined the relationship between group membership based on corticosteroid versus corticosteroid naïve or cluster membership and functional measures commonly used to define disease progression in boys with Duchenne muscular dystrophy. Determining the relationship between gait patterns and specific markers of disease progression will help clinicians determine potential treatment options aimed at enhancing function and maintaining the ability to walk as long as possible.

Methods

Forty-four children met the inclusion criteria for this longitudinal multicenter study. One child did not complete all of the assessments; thus, 43 children were included in the analysis. Participants were boys 4 years of age or older who were able to walk independently for 5 minutes at self-selected speed and were able to understand directions for testing procedures. All had a diagnosis of Duchenne muscular dystrophy as determined by clinical evaluation, family history, blood DNA studies demonstrating elevated serum creatine phosphokinase levels, or confirmation with muscle biopsy. All participants completed a quantitative gait analysis (VICON, Oxford Metrics Ltd, Oxford, England; and Motion Analysis Corporation, Santa Rosa, CA), assessments of walking velocity and gait efficiency (Cosmed K4b² unit, Santa Rosa, CA), and measurement of gross motor function (Gross Motor Function Measure-66¹³) and timed motor performance (time to run 10 meters, time to climb 4 stairs).

The institutional review boards of both participating hospitals approved this study, all parents/guardians gave informed consent, and participants provided assent.

Dynamic joint motion was assessed using either a VICON 612 (Oxford Metrics Ltd, Oxford, England) or a Motion Analysis Corporation (Santa Rosa, CA) motion measurement system. Joint kinematics were analyzed at 1 hospital (Shriners Hospitals for Children-Portland) using the Plug-in Gait model within VICON Workstation (Oxford Metrics Ltd, Oxford, England). Passive retroreflective markers were applied according to the Plug-in Gait model (Oxford Metrics Ltd, Oxford, England). The upper extremity and trunk markers were applied in accordance with the model described by Rab et al.¹⁴ All testing was performed at the child's self-selected velocity. Kinematic graphs were plotted to examine the consistency of the pattern, and 1 representative cycle was used for analysis. Because deviation from normal kinematic gait patterns can be evaluated for both the left and the right, the side chosen for analysis was based on handedness.

Energy efficiency was measured with the Cosmed K4b², which allows for simultaneous collection of expiratory minute ventilation, volume of oxygen, volume of carbon dioxide, and heart rate. The Cosmed K4b² was calibrated for oxygen and carbon dioxide concentration, turbine flow, and delay before each patient testing, according to manufacturer's recommendations. Subjects had not eaten for a minimum of 4 hours before testing. The evaluation consisted of a 10-minute rest period in a semi-recumbent position followed by a 10-minute walk at their self-selected velocity around a 33-meter track or down a 30-meter hallway. All oxygen values were determined during 5 minutes of steady state during the resting and walking portions of the test. Steady state was defined as less than a 10% variation in volume of oxygen and expiratory minute ventilation and a 5% variation in the respiratory quotient, which is the volume of carbon dioxide over the volume of oxygen. Velocity was determined by the distance walked per minute with the mean of the 5 steady state minutes used in the analysis. Net nondimensional cost was used as the measure of energy, because it subtracts resting energy consumption from walking, leaving only the energy increment needed for walking, and it incorporates nondimensional scaling to account for stature, thus reducing the impact of growth and intersubject variability. The same 5 minutes of steady state were used to determine the net nondimensional cost.

Function was evaluated using timed motor performance tests (time to run 10 meters and climb 4 stairs) and the standing (dimension D), walking, running, and jumping (dimension E) sections of the Gross Motor Function Measure. For the timed motor tasks of running 10 meters and climbing 4 stairs, the boys were instructed to complete the task as quickly as possible, with time to complete recorded in seconds. Scoring for the Gross Motor Function Measure is based on the child's ability to initiate, partially complete, or complete a task.¹³ The composite score for the Gross Motor Function Measure-66 was used in the analysis.

Data were analyzed using the Statistical Package for the Social Science software (SPSS version 17.0, SPSS Inc., Chicago, IL). Pearson correlation coefficients were used to determine the relationship between gait deviation index, functional, and energy efficiency variables, while Spearman rho was used to determine the relationship between corticosteroid use and gait deviation index, functional, and energy efficiency variables. Gait patterns were evaluated using 2 methods: corticosteroid vs corticosteroid naïve (boys whose families chose not to receive corticosteroid treatment) and by cluster analysis based on gait deviation. Cluster analysis, using a k-means algorithm of the 15 gait feature scores of the gait deviation index, was used to stratify groups based on the severity of their gait deviations from normal.¹¹ Cluster analysis provides an objective, quantitative classification system by separating individuals into homogenous groups based on the selected group of input parameters.⁶ The k-means technique divides a set of input parameters into a predetermined

number of groups by maximizing variability between clusters and minimizing the variability within a cluster.⁵

Independent samples *t* test was used to determine whether significant differences in functional variables exist between boys taking corticosteroids and boys who were corticosteroid naïve, while a 1-way analysis of variance was used to determine whether there were significant differences in functional variables between the boys in each of the clusters. When significant differences were found, Scheffé post hoc tests were used to determine where significant differences occurred. Significance was set at $P < .05$.

Results

Group Relationships

There was a significant negative correlation between Gross Motor Function Measure-66 and the timed motor performance tests of run 10 meters ($r = -.705$) and climbing 4 stairs ($r = -.639$), indicating that, as gross motor function increased, the time to complete motor tasks decreased. Similarly, a significant negative relationship was seen between time to run 10 meters and velocity ($r = -.479$). Thus, as velocity increased, the time to run 10 meters decreased. A negative relationship was also seen between velocity and net nondimensional cost ($r = -.702$), indicating that as velocity increased, net nondimensional cost decreased. A significant positive relationship was seen between Gross Motor Function Measure-66 and velocity ($r = .382$) (Table 1), indicating that, as the ability to perform gross motor skills increased, velocity increased.

There was a significant positive relationship between time to run 10 meters and the time to climb 4 stairs ($r = .546$), and time to run 10 meters and net nondimensional cost ($r = .468$). There was a significant positive relationship between velocity and gait deviation index ($r = .302$), indicating that as velocity increased the gait pattern became more normal. There were no correlations between corticosteroid use and any of the functional variables.

Comparison Based on Corticosteroid Use

Comparing the boys on the basis of corticosteroid use, those taking corticosteroids were an average of 17 months older, 8 cm taller, and 6 kg heavier; however, these differences were not statistically significant (Table 2). A comparison of joint motion for the boys on corticosteroids and those who are corticosteroid naïve demonstrates similar deviations from normal as demonstrated by the similarity of their gait deviation index scores, 77.3 and 78.7, respectively (Figure 1). No significant differences were found between the functional variables for boys taking corticosteroids and those who were corticosteroid naïve (Table 3).

The corticosteroid naïve group demonstrated a slight decrease in anterior pelvic tilt, increase in pelvic rotation, and greater external rotation of the hip compared with the boys taking corticosteroids and normal controls. Boys taking corticosteroids had a slight increase in hip adduction during initial stance, which was associated with a rise of the pelvis at the same time. The remainder of joint motion at the pelvis, hip, knee, and ankle were similar between the boys taking corticosteroids and those who were corticosteroid naïve. In comparison with norms, both groups of boys had a decrease in hip flexion from initial contact to midstance and again at late swing. At the knee, there was a decrease in flexion during loading response, with an increase in flexion from midswing to terminal swing. The ankle demonstrated plantarflexion at initial contact, followed by a slight decrease in maximum dorsiflexion at midstance, and decreased dorsiflexion during swing.

Comparison Based on Gait Pattern Deviation

Cluster analysis identified 3 patterns based on the similarity of their gait deviations from normal (Figure 2). Boys taking corticosteroids and corticosteroid naïve boys were in all clusters. The boys in the mild group were approximately 16 to 19 months younger than the boys in the moderate and advanced groups (Table 2). Although the finding was not statistically significant, boys in the moderate and advanced groups were taller and heavier than boys in the mild group, which is related to age differences. Differences were noted in gait deviation index scores among clusters, specifically the mild group (85.0) versus the moderate (gait deviation index = 74.8, $P = .10$) and advanced (gait deviation index = 69.6, $P = .06$) groups; however, these were not statistically significant. While differences in the magnitude of functional variables were seen between the 3 clusters, with the mild group having the greater function, fastest velocity, and lowest energy cost, these differences were not statistically significant (Table 4).

Gait patterns by cluster demonstrated subtle differences in joint motion at the hip, knee, and ankle. For the boys in the mild group, the pelvis had a posterior pelvic tilt in comparison to normal, with fairly normal obliquity and rotation. Subsequently, hip motion demonstrated a decrease in hip flexion during stance that continued through the swing phase, with normal hip adduction and rotation. Knee motion was fairly normal, with only a slight decrease in knee flexion at loading response. Normal ankle motion during stance was seen in the boys in the mild group, while a moderate drop foot was noted during swing.

The boys in the moderate group had a slight increase in anterior pelvic tilt in comparison to normal, with normal pelvic obliquity and increased pelvic rotation pattern. Boys in the moderate group demonstrated normal hip flexion during initial stance and late swing; however, there was a lack of full extension during late stance. Coronal and transverse plane motion demonstrated normal hip adduction and external hip rotation. Knee motion during loading response was slightly decreased, with normal knee extension during late stance. Ankle motion was normal during stance, with only a slight drop foot during swing.

The gait pattern of the boys in the advanced group demonstrated normal pelvic tilt and obliquity, with an increase in internal pelvic rotation. For the boys in the advanced group, hip flexion was decreased during initial stance, with a decrease in adduction. Knee motion demonstrated minimal knee flexion during loading response, with normal motion during swing. Ankle motion demonstrated an increase in dorsiflexion during early stance and decreases in dorsiflexion during late stance. Excessive drop foot during swing was noted for the boys in the advanced group.

Discussion

Balaban and colleagues reported that the use of corticosteroids improves muscle strength and delays the loss of independent ambulation between 2 and 3 years.² In the current study, boys with Duchenne muscular dystrophy who were older and taking corticosteroids demonstrated gait patterns similar to those who were younger and not taking corticosteroids, which can indicate that corticosteroids affect muscle strength and, subsequently, gait pattern.² These findings are supported by D'Angelo et al, who reported that the gait patterns of boys taking corticosteroids and those who were corticosteroid naïve were fairly similar, with no significant differences between the groups except for ankle power, which was significantly greater in the boys taking corticosteroids.⁹ During the early phase of disease progression, gait changes in boys with Duchenne muscular dystrophy are subtle, consisting of an increased shift of the trunk toward the stance-phase limb (abductor lurch), loss of the initial knee flexion wave with weight acceptance, and lack of heel contact during stance phase, with an increased foot drop in swing.^{9,15,16} The decrease in knee flexion noted in

both groups of boys can be explained as a compensatory mechanism for quadriceps weakness, while the increase in knee flexion during swing is a compensatory mechanism for weakness of the dorsiflexors, which results in the inability to achieve full dorsiflexion during swing.

Sutherland et al used principal component analysis to identify key gait variables for cluster analysis of boys with Duchenne muscular dystrophy to determine whether distinct patterns of gait deviations existed.¹⁶ They initially found 2 distinct clusters, which were defined as the “early group” and the “transition group”¹⁶; however, not all children could be classified into 1 of the 2 groups. Linear discrimination of the subset of nonclassified children assisted in allocating children to appropriate groups and subsequently resulted in a third group, which they defined as the late phase. As individuals with Duchenne muscular dystrophy moved from the early to late phase, the gait pattern demonstrated an increase in anterior pelvic tilt, maximum hip flexion in swing, and maximum internal foot rotation in stance, while maximum hip extension in stance and ankle dorsiflexion in swing decreased.¹⁶ Similarly, the gait parameters of velocity and cadence significantly decreased as boys progressed from the early to transitional phase of gait pattern. The boys in the current study, when classified by clusters, also demonstrated 3 groups and similar patterns of gait pattern transition, with the mild group having an overall gait pattern most similar to norm, while the advanced group demonstrated the greatest deviation. While there are some subtle differences in the gait patterns found by the method of cluster analysis by Sutherland et al and those found in our study, this can be the influence by the use of corticosteroids in many of the boys with Duchenne muscular dystrophy in our group of boys.

The progression in gait deviations found in our study and that of Sutherland et al can be explained by the compensatory mechanisms that result from muscle weakness and the need to balance the center of mass within the center of pressure. As muscle weakness progresses, stability during single limb stance is threatened and boys with Duchenne muscular dystrophy lose the ability to control the momentary imbalances that occur during normal walking, leading them to cease walking.¹⁶ In relationship to function, boys with the lowest gait deviation index score, the advanced group, have the slowest velocity and the highest energy cost. Boys with the highest gait deviation index score, the mild group, have the highest Gross Motor Function Measure, fastest velocity, and lowest energy cost. The results of this study demonstrate that, in boys with Duchenne muscular dystrophy, gait pattern deviations are related to function, which can provide further insight into the understanding of disease progression. Sutherland et al noted that age alone was an unreliable index of disease progression because, among individuals with Duchenne muscular dystrophy, there are differences in muscle weakness, contractures, motivation to remain ambulatory, and body weight; however, changes in gait patterns reflect all of these factors.¹⁶

While the Gross Motor Function Measure has not been used to assess function in boys with Duchenne muscular dystrophy, it has been validated for individuals with spinal muscular atrophy.¹⁷ In that study, the Gross Motor Function Measure was found to be a better discriminator of ambulatory status than quantitative muscle testing in individuals with spinal muscular atrophy.¹⁷ The high correlation between Gross Motor Function Measure, timed motor variables, and velocity found in this study is expected, and is similar to the correlations between velocity and clinical evaluations of function found in children with neuromuscular impairments and cerebral palsy.¹⁸ The lack of relationship between corticosteroid use and any of the functional variables demonstrates that boys who are taking corticosteroids who are older are functioning at a level similar to that of the younger corticosteroid naïve; however, both groups of boys are fairly young and loss of ambulation is not imminent. It is important to follow this relationship longitudinally to determine at what age the boys with Duchenne muscular dystrophy begin to differ and whether

corticosteroid use impacts the relationship among these variables. Biggar and colleagues reported that evaluation of the boys in the second decade of their life demonstrates the impact that deflazacort has on their health and quality of life for boys with Duchenne muscular dystrophy.³

Further study is needed to determine whether the gait deviation clusters identified in this study are indicative of a progressive pattern of muscle weakness and reveal differences in the manifestation of Duchenne muscular dystrophy, which can assist with recommendations for treatment. Additionally, evaluation of trunk kinematics and lower extremity joint moments and powers will provide greater insight into the subtle changes that are occurring as a result of muscle weakness, which have not yet manifested as a loss in gross motor movements. A larger sample size is needed to determine the impact of corticosteroid use on the progression of gait deviation patterns and function. During the ages of 9 to 12 years, proximal muscle weakness progresses and gait becomes more abnormal and most boys stop walking.¹ The boys in the current study range in age from 4 to 15 years; therefore, following these boys until the cessation of walking will provide insight into the progression of the disease and how it can be altered by corticosteroid use or other potential therapeutic interventions, such as surgery or orthotics.

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Joint Rotation Angles

Figure 1.
Kinematic patterns by corticosteroid use.

Joint Rotation Angles

Figure 2.
Kinematic patterns by gait deviation cluster.

Table 1
Correlation Between Corticosteroid Use, Gait Deviation, Functional Measures, and Energy Cost

	Corticosteroid	GDI	GMFM-66	Run 10 m	Climb 4 Stairs	Velocity	NNcost
Corticosteroid	1.0						
GDI	.075 $P = .56$	1.0					
GMFM-66	-.031 $P = .82$	.276 $P = .08$	1.0				
Run 10 m	.034 $P = .80$	-.291 $P = .07$	-.705 ** $P < .01$	1.0			
Climb 4 stairs	.085 $P = .51$	-.06 $P = .71$	-.639 ** $P < .01$	.546 ** $P < .01$	1.0		
Velocity	.000 $P = 1.0$	.302 * $P = .05$	.382 * $P = .01$	-.479 ** $P < .01$	-.267 $P = .09$	1.0	
NNcost	-.013 $P = .92$	-.140 $P = .37$	-.298 $P = .06$	.468 ** $P < .01$	.115 $P = .47$	-.702 ** $P < .01$	1.0

Abbreviations: GDI, gait deviation index; GMFM-66, Gross Motor Function Measure-66; NNcost, net nondimensional cost.

Shading denotes correlations that are significant at $P < .05$ or less.

* $P < .05$.

** $P < .01$.

Table 2

Demographics of DMD Boys by Corticosteroid Usage and Cluster Grouping

Variable	Corticosteroid Usage		Gait Deviation Clusters		
	Naïve Mean (SD)	Corticosteroid Mean (SD)	Mild Mean (SD)	Moderate Mean (SD)	Advanced Mean (SD)
Number of boys (n)	15	28	19	15	9
Age, months	85 (36)	102 (28)	86 (28)	105 (34)	102 (33)
Height, cm	118 (19)	126 (12)	119 (10)	126 (18)	127 (19)
Weight, kg	26 (16)	32 (14)	25 (8)	35 (17)	33 (20)
Corticosteroid naïve/Corticosteroid			7/12	5/10	3/6

Abbreviations: DMD, Duchenne muscular dystrophy; SD, standard deviation.

Table 3

Functional Variables by Corticosteroid Usage

Variable	Corticosteroid Usage	
	Corticosteroid Naïve Mean (SD)	Corticosteroid Mean (SD)
Number of boys (n)	15	28
GMFM-66	70 (7)	70 (7)
Time to run 10 m (s)	6.57 (3.3)	6.19 (2.1)
Time to climb 4 stairs (s)	4.68 (2.3)	5.78 (3.9)
Velocity (m/s)	.733 (.22)	.758 (.18)
NNcost	.364 (.17)	.342 (.12)
GDI	77.28 (14.08)	78.71 (15.77)

Abbreviations: GDI, gait deviation index; GMFM-66, Gross Motor Function Measure-66; NNcost, net nondimensional cost; SD, standard deviation.

Table 4

Functional Variables by Gait Deviation Clusters

Variable	Gait Deviation Clusters		
	Mild Mean (SD)	Moderate Mean (SD)	Advanced Mean (SD)
Number of boys (n)	19	15	9
GMFM-66	71.8 (8)	69.4 (6)	66.0 (4)
Time to run 10 m (s)	6.0 (2)	5.7 (2)	7.97 (3)
Time to climb 4 stairs (s)	5.7 (4)	4.8 (3)	5.7 (3)
Velocity (m/s)	.77 (.13)	.76 (.25)	.68 (.21)
NNcost	.310 (.07)	.363 (.15)	.411 (.21)
GDI	84.96 (14)	74.8 (13)	69.57 (14)

Abbreviations: GDI, gait deviation index; GMFM-66, Gross Motor Function Measure-66; NNcost, net nondimensional cost; SD, standard deviation.