How should the margin of stability during walking be expressed to account for body size?

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Abstract

Introduction: When expressing the margin of stability (MOS) as a distance, the MOS magnitude has an unclear mechanical interpretation, and it is unknown how body mass and height may influence the measure. In this study, we applied different expressions of the MOS, including that of an impulse, a change in center of mass (COM) velocity, and a scaled, unitless impulse value. The purpose of this study was to determine the influence of body size on these stability margin expressions using walking data from both children and adults. We anticipated that stability margins expressed as an impulse would have strong correlations with body mass and height, as well as large differences between groups. We predicted that scaling for body size would result in weaker correlations and smaller between-group effect sizes. **Methods:** We calculated each stability margin at the point of minimum lateral values of stance and in the anterior direction at mid-swing. **Results:** In the anterior direction, the scaled unitless impulse was the only margin to have non-significant relationships with body size (r=-0.10 and -0.08, p>0.05) and small between group effect sizes (d=0.31, p=0.40). In the lateral direction, the MOS, change in velocity margin, and scaled, unitless impulse margin had non-significant correlations (r=-0.20 to 0.17, p>0.05) with body size and small-to-moderate between group differences (d < 0.44, p>0.05). **Discussion:** We propose using impulse to measure stability margins, as it has has the mechanical implications of the impulse needed to change stability states. If scaling is needed, we encourage using the scaled, unitless impulse.

Keywords: Dynamic Stability, Walking, Gait, Scaling, Balance

1. Introduction

Stability can be defined as the ability to control the body's center of mass (COM) relative to the base of support in quasi-static and dynamic conditions (Gill-Body et al., 2021). The margin of stability (MOS) is a measure that reflects the relationship of the COM relative to the edge of the base of support (BOS) (Hof et al., 2005). The BOS is defined as the boundary around the foot or the feet in contact with the ground. This COM-BOS relationship has implications for stability, as it reflects the initial conditions should a perturbation occur to disrupt the COM-BOS relationship. Conceptually, the *MOS* is the distance between an individual's extrapolated center of mass (*xCOM*, Equation 1), an estimated location that accounts for the COM's position and scaled velocity, and the edge of their BOS (Hof et al., 2005).

$$xCOM = COM + \frac{v_{COM}}{\sqrt{\frac{g}{l}}} \quad (1)$$

where the body's COM horizontal velocity (v_{COM}) is scaled by the eigenfrequency of an inverted pendulum, comprised of gravity (g) and a pendulum length (l). A positive *MOS* occurs when the *xCOM* is within the border of the BOS, suggesting a state of stability. A negative *MOS* occurs when the *xCOM* is beyond the border suggesting a fall will occur unless stability is recovered through counter-rotating segments about the COM, taking a step to reposition the edge of the BOS, and/or applying an external force such as that from a handrail (Hof, 2007).

A limitation of the *MOS* is that, when expressed as a distance, it has an unclear mechanical interpretation. The magnitude of the *MOS* is proportional to the perturbation magnitude needed to change stability states, assuming similar balance-reaction capabilities across participants (Hof et al., 2005). How does a measure of distance between a theoretical point (*xCOM*) and the BOS edge represent that perturbation magnitude? In this short communication, we propose expressions of the *MOS* in units that have a more explicit mechanical meaning to represent the perturbation magnitude needed to change stability states.

When introducing the *MOS* concept, Hof et al. (2005) also proposed a measure of *impulse* (J_s, Equation 2):

$$J_s = m\sqrt{\left(\frac{g}{l}\right)} \cdot MOS \quad (2)$$

where *m* is the mass of the individual. To our knowledge, no subsequent studies have used this impulse measure, despite its clear implications regarding the perturbation magnitude that can change stability states. We suggest that this impulse value J_s holds more biomechanical meaning than the *MOS* value of distance.

It is clear from Equation 2 that, given the same *MOS*, the impulse stability margin (J_s) increases linearly with body mass. The influence of height on J_s is less straightforward, as Equations 1 and 2 are both influenced by pendulum height. This effect of height is dependent on the magnitude and direction of the COM velocity (v_{com}). In stable circumstances (i.e., positive *MOS*) where v_{com} is directed towards the BOS edge, a larger pendulum length is associated with a smaller J_s. These influences of height and mass agree with the common consensus that heavier, shorter objects are more stable.

It is our perspective that the *MOS* is a partially scaled version of J_s (Equation 2). To account for body mass and height, other expressions of stability can be calculated, including the *change in COM velocity* (*Δv_s*) needed to change stability states:

$$\Delta v_s = \frac{J_s}{m} = \sqrt{\frac{g}{l}} \cdot MOS \quad (3)$$

Or a *scaled, unitless* J_s value:

$$\widehat{J_s} = \frac{J_s}{m \cdot \sqrt{g l_0}} = \frac{MOS}{l_0} \quad (4)$$

where l_0 is a scaling factor. The extent to which body mass and height influence these expressions of stability margins during gait is unknown.

The purpose of this study was to determine the influence of body size on the aforementioned expressions of the stability margins. We used walking data from previous studies with children and adults, providing us with a wide range of body masses and heights. We assessed how each stability margin, determined at minimum lateral values and anterior mid-swing values, correlated with body mass and height. We also evaluated the between-group effect sizes of each measure. We predicted that, because of the direct influence of mass and height (Equation 2), stability margins expressed as an impulse would have strong correlations with body mass and height as well as large between-group differences. We predicted that, by fully or partially scaling for body size, the other expressions of stability margins would have reduced correlations and between-group effect sizes. Under the assumption that all participants walked with geometric similarity, we predict that the scaled impulse measure ($\widehat{J_s}$) would hold weak correlations with height and mass and between-group differences would be small.

2. Methods

2.1 Participants

This study is a secondary analysis of two previously conducted studies done on a group of children and adults. Datasets included fourteen typically developing children (Table 1) (Tracy et al., 2019) and 16 neurotypical adults (Table 1) (Christensen, 2020). Participants reported no diagnosed genetic disorder or recent injury that altered mobility or balance. Both studies were approved by the University of Delaware Institutional Review Board. All children provided verbal assent with the legal guardians and adult participants providing informed consent.

2.2 Procedure

In both studies, participants wore the same whole-body configuration of 41 retroreflective or virtual markers distinguishing the extremities, pelvis, trunk, and head. The marker trajectories were recorded (Qualisys, Göteborg, Sweden, 120 Hz) as participants walked at self-selected, preferred speeds (Table 1) across a 10-m walkway. The first six recorded trials for each participant were analyzed.

2.3 Data Analysis

The MOS was calculated using custom MATLAB software (MathWorks, Natick, MA, USA, R2021b) at two key points in the gait cycle. The MOS was evaluated in the anterior direction at mid-swing—where a trip is likely to occur (Schulz, 2017)—defined as the point where the swing limb and the stance limb toe markers were aligned (Tracy et al., 2019). The minimum lateral MOS was also evaluated (Tracy et al., 2019) which represents the point of least stability in the lateral direction. The stability margins were calculated for each limb and averaged across all strides for data analysis. Segment center of mass locations were determined using anthropometric estimates (Dempster, 1955). Pendulum lengths were defined as the distance between the whole-body COM and the ankle joint center at the timepoint of interest. The edge of the BOS was defined by the toe marker. Expressions of the stability margins were calculated as the *MOS*, J_s, Δv_s, and the $\widehat{J_s}$ (Equations 1–4), using pendulum length as the scaling factor (l_0) for $\widehat{J_s}$.

2.4 Statistical Analysis

The relationships between the different stability margin expressions and body mass or height were evaluated using Pearson's product moment correlations (r). Independent t-tests and Cohen's d effect sizes were used to compare the stability margins between children and adults. All statistical analyses were done using SPSS (IBM, Armonk, NY, v25).

3. Results

3.1 Margin of Stability

The anterior margin of stability (*MOS)* had strong correlations with height (r=-0.75, p<0.01) and mass (r=-0.69, p<0.01) and a strong between-group effect size (d=1.63, p<0.01). The minimum *MOS* in the lateral direction had non-significant correlations with body mass (r=0.17, p=0.37) and height (r=0.14, p=0.48) and weak between-group effect sizes (d=-0.10, p=0.80).

3.2 Impulse Margin

In the anterior direction, impulse (J_S) had the strongest correlations with both body height and mass (Table 2, Figure 1) and between-group effect size (d=2.62, p<0.01). At the point of the minimum lateral *MOS*, lateral J_S had the strongest correlations with both body height and mass (Table 2, Figure 2) and between-group effect size (d=-1.07, p<0.01).

3.3 Change in Velocity Margin

In the anterior direction, the expression of change in velocity (Δv_S) and were significantly different between children and adults for height (r=-0.53, p<0.01) and mass (r=-0.48, p<0.01) and between-group effect sizes (Table 2, Figure 2). At the point of the minimum lateral MOS, lateral Δv_S had the weakest correlations with mass and height and also the weakest between-group effect sizes (Table 2, Figure 2).

3.4 Scaled Impulse Margin

In the anterior direction at mid-swing, scaled impulse ($\widehat{J_S}$) had the weakest correlations with mass (r=-0.08, p=0.67) and height (r=-0.40, p=0.61) and the weakest between-group effect sizes (Table 2, Figure 1). At the point of the minimum lateral MOS the lateral $\widehat{J_S}$ had non-significant correlations with body mass (r=-0.13, p=0.48) and height (r=-0.20, p=0.30) and weak between-group effect sizes (Table 2, Figure 2).

4. Discussion

The purpose of the study was to determine the influence of body mass and height on the different expressions of stability margins related to the MOS. We predicted that impulse stability margins (J_S) would have strong correlations with body mass and height, as well as large between-group differences. This prediction was supported. We predicted that, by fully or partially scaling for body size, the other expressions of stability margins would have reduced correlations and between-group effect sizes. This prediction was partially supported in the anterior direction as the scaled impulse significantly reduced the correlation between body mass and height, but not for the change in velocity measure. In the lateral direction, fully or partially scaling impulse significantly removed the correlation with the body parameters. The unitless values of scaled impulse ($\widehat{J_S}$) eliminated significant correlations with body size, as well as group differences between children and adults.

We demonstrated that the conclusions of a study, such as whether adults and children walk with different stability margins, are altered with the expression of stability (Figure 1-2). The appropriate expression for a study is dependent upon its design (e.g., within- or between-participant comparisons). There are numerous considerations for how body size may affect fall risk or a laboratory study of balance. The size of a destabilizing impulse in the free-living environment or laboratory can be dependent upon the size of an individual. Considering people of different body masses, a walking collision with a rigid object, such as a wall, would result in a larger destabilizing impulse for people with more mass, assuming consistent initial velocities across participants. In laboratory contexts, controlled perturbations may be prescribed based on the horizontal force of a pull (Schulz et al., 2005) or push (Hof et al., 2010). Those forces may be constant across participants (Hof et al., 2010) or scaled to body mass (Schulz et al., 2005), the choice of which would affect the resulting acceleration of people with different body masses. Considering people of different body heights, if those forces are applied at the waist or torso, they generate larger destabilizing torques about the ankle for a taller person. Perturbations may also be delivered as horizontal support-surface accelerations. Assuming equivalent surface accelerations across body sizes, a person with more mass would receive a larger perturbing force. For a taller person, those forces would generate larger destabilizing torques about the whole-body COM (Crenshaw and Kaufman, 2014). Additionally, the balance reaction (i.e. stabilizing impulse) may also be related to body size. Static and dynamic muscle torque is related to body mass (Bober, 1990; Jaric et al., 2002). Therefore, larger individuals may be able to withstand larger perturbations due to their ability to generate larger corrective muscle torques. It is unclear how these two factors (i.e., larger destabilizing torques and greater corrective capacities) interact to affect fall risk. While choosing an expression of a stability margin, we suggest considering how body size may be different across study comparisons, how destabilizing perturbations may be different across body sizes within and outside of the lab, and how body size influences the response to destabilizing perturbations.

We chose pendulum length (l_0) as our scaling factor because the inverted pendulum model is the basis for the *MOS* measure (Hof, 2018). Leg length has been proposed as the appropriate scaling factor for gait parameters (Hof, 2018), but other variables have been used. Pierrynowski and Galea (2001) scaled gait variables by several scaling methods, including dimensionless numbers and hydrodynamic, geometric, dynamic, and static stress strategies. They concluded that scaling by the ad hoc (body mass or leg length) or to a dimensionless value had the smallest inter-participant variability. We propose the use of the dimensionless value for scaling, but future, larger studies are needed to determine if other strategies reduce inter-participant variability to a greater extent.

This analysis assumes geometric similarity across children and adults. However, Froehle et al. (2013) observed in a longitudinal study that gait parameters change throughout childhood, including alterations in the duration of single-limb stance, cadence, step length, and the ratio of pelvic span to ankle spread. Therefore, we cannot conclude that observed differences in stability margins are due to body size alone. Different control strategies may be in place across ages, and our results do not provide insight into that *control* of stability during walking. Hof (2008) expanded upon the MOS concept by showing that a change in foot placement can be enacted in response to a scaled change in velocity of the COM. Therefore, expressing stability margins as a length has value in characterizing foot placement. We do not know if people walk with targeted stability margins (i.e., J_S, *MOS*, Δv_S, or $\widehat{J_S}$) or which expression of stability best corresponds with step-to-step foot placement across participants with a range of heights and masses.

An alternative approach to scaling is to consider confounders as covariates, such as height or mass when comparing groups. We compared the impulse margin (J_S) of children and adults with this approach, using two separate ANCOVA models due to the multicollinearity of mass and height (the correlation between height and mass was r=0.95). In the anterior direction, there were no significant differences in J_S between children and adults after accounting for height (p=0.20) or mass (p=0.85). In the lateral direction, there were also no significant differences in J_S between children and adults after accounting for height (p=0.95) or mass (p=0.46). Therefore, the scaling and statistical approaches resulted in the same conclusion. Some populations with a high risk of falling are also characterized by atypical body sizes, including pregnant women (Dunning et al., 2010; Mitchell et al., 2014) and obese adults (Allin et al., 2016). We suggest that scaling a stability margin measure, as done in this analysis, accounts for the *mechanical* influence of body size on stability margins. A statistical approach of including body size as a covariate will adjust for factors that go beyond pure mechanical influence such as physiological factors that underly fall risk that also correlate with body size.

Gait speed has a direct influence on anterior stability margins. Children and adults walked with different absolute gait speeds (p<0.01, Table 1), and those gait speeds were significantly correlated with anterior impulse (J_s; *r*=-0.74, p<0.01). When controlling for gait speed as a covariate, significant differences between the J_s of children and adults persisted (p<0.01). Therefore, accounting for speed does not eliminate a potential need for scaling.

5. Conclusion

In this study, we presented several expressions of stability margins that are related to the MOS. We demonstrated that scaling stability margins reduced differences between children and adults in both the anterior and lateral directions. We suggest using stability impulse (J_s) or the scaled impulse ($\widehat{J_s}$) expression in future research studies, depending on the research question, study design, and implication of results. It is our opinion that the impulse margin (J_s) holds the strongest mechanical meaning in terms of perturbation magnitude that can change stability states. If between-participants comparisons must be made, or if body size changes in a longitudinal study, we encourage scaling that impulse value to a unitless expression ($\widehat{J_s}$). We further recommend always including scaled, unitless impulse to allow for cross study comparisons.

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Conflict of Interest Statement:

The authors declare that they have no conflict of interest.

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Figures:

Table 1: Participant Demographics.

	Typically Developing Children (N=14; 7 females)	Neurotypical Young Adults (N=16; 9 females)
Age (years)	9.1 (2.6)	21.4 (3.6)
Height (m)	1.33 (0.19)	1.74 (0.10)
Mass (kg)	30.8 (11.5)	65.1 (13.0)
Gait Speed (m/s)	1.2 (0.2)	1.4 (0.1)
Gait Speed (statures/s)	0.93 (0.12)	0.82 (0.11)

Table 2: Variable expression value correlations with body size, and between-group differences in stability between children and adults.

Direction and Time Point	Variable expression	Correlation (Pearson's r)		Mean (SD) Values		Between Group Effect Size (Cohen's d)
		Height	Mass	Children	Adults	
Anterior at Mid-swing	J_s (N·s)	-0.92**	-0.94**	-25.50 (12.5)	-64.2 (16.5)	2.62**
	Δv_s (cm/s)	-0.53**	-0.48**	-80.4 (14.3)	-98.6 (18.4)	1.09**
	MOS (cm)	-0.75**	-0.69**	-21.0 (4.79)	-29.6 (5.69)	1.63**
	$\hat{J}$ (unitless)	-0.10	-0.08	-31.7 (5.44)	-33.5 (6.24)	0.31
Minimum Lateral	J_s (N·s)	0.58**	0.66**	2.56 (2.08)	4.67 (1.89)	-1.07**
	Δv_s (cm/s)	-0.04	0.01	7.84 (5.06)	7.16 (2.44)	0.17
	MOS (cm)	0.14	0.17	2.03 (1.30)	2.13 (0.76)	-0.10
	$\hat{J}$ (unitless)	-0.20	-0.13	3.10 (2.02)	2.44 (0.83)	0.44

** p<0.01

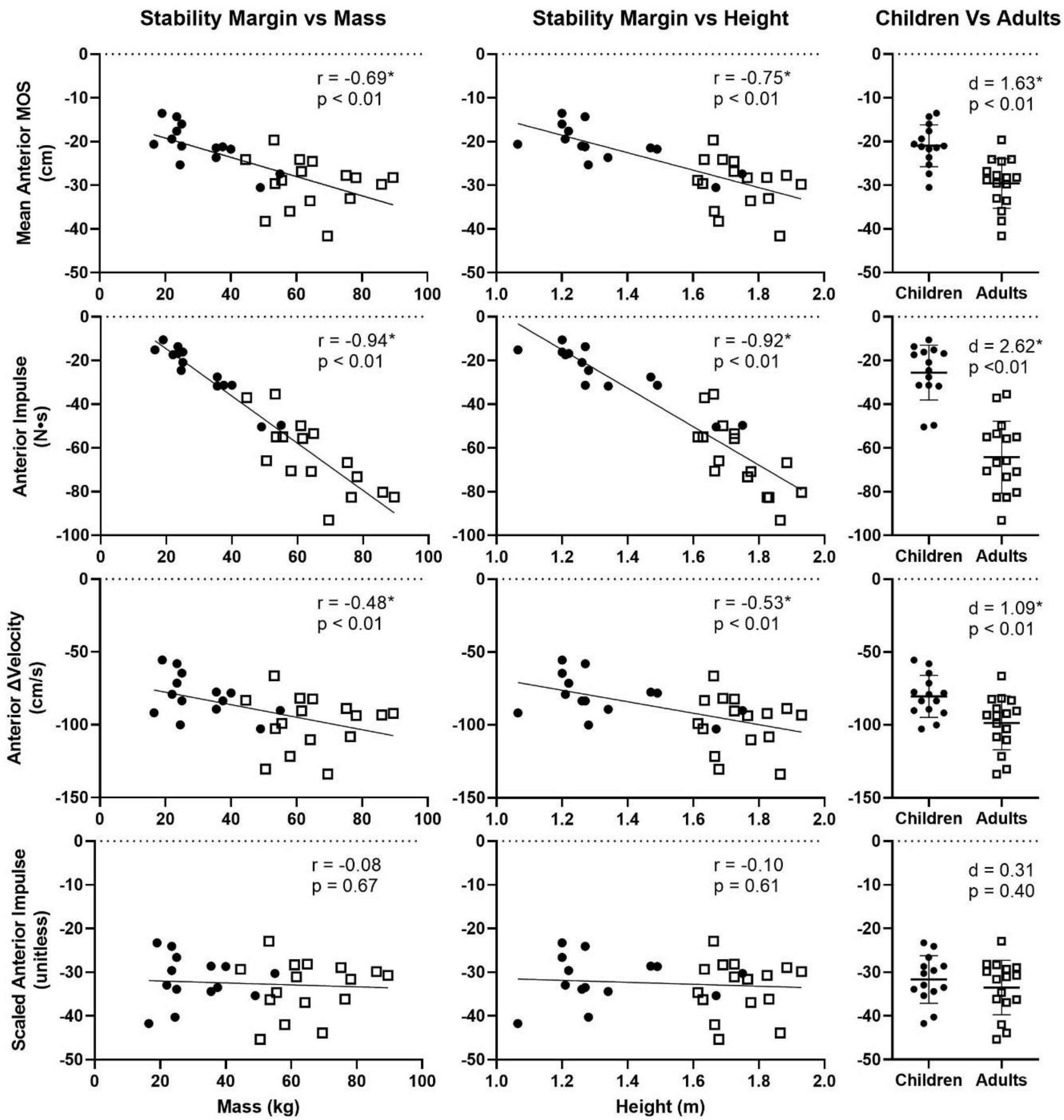

Figure 1: Anterior stability margin expressions at mid-swing correlated with mass (left column), correlated with height (middle column), and compared between children and adults (right column). Closed circles represent typically developing children and open squares represent neurotypical young adults. Pearson r and Cohen d values that are statistically significant are denoted with an asterisk.

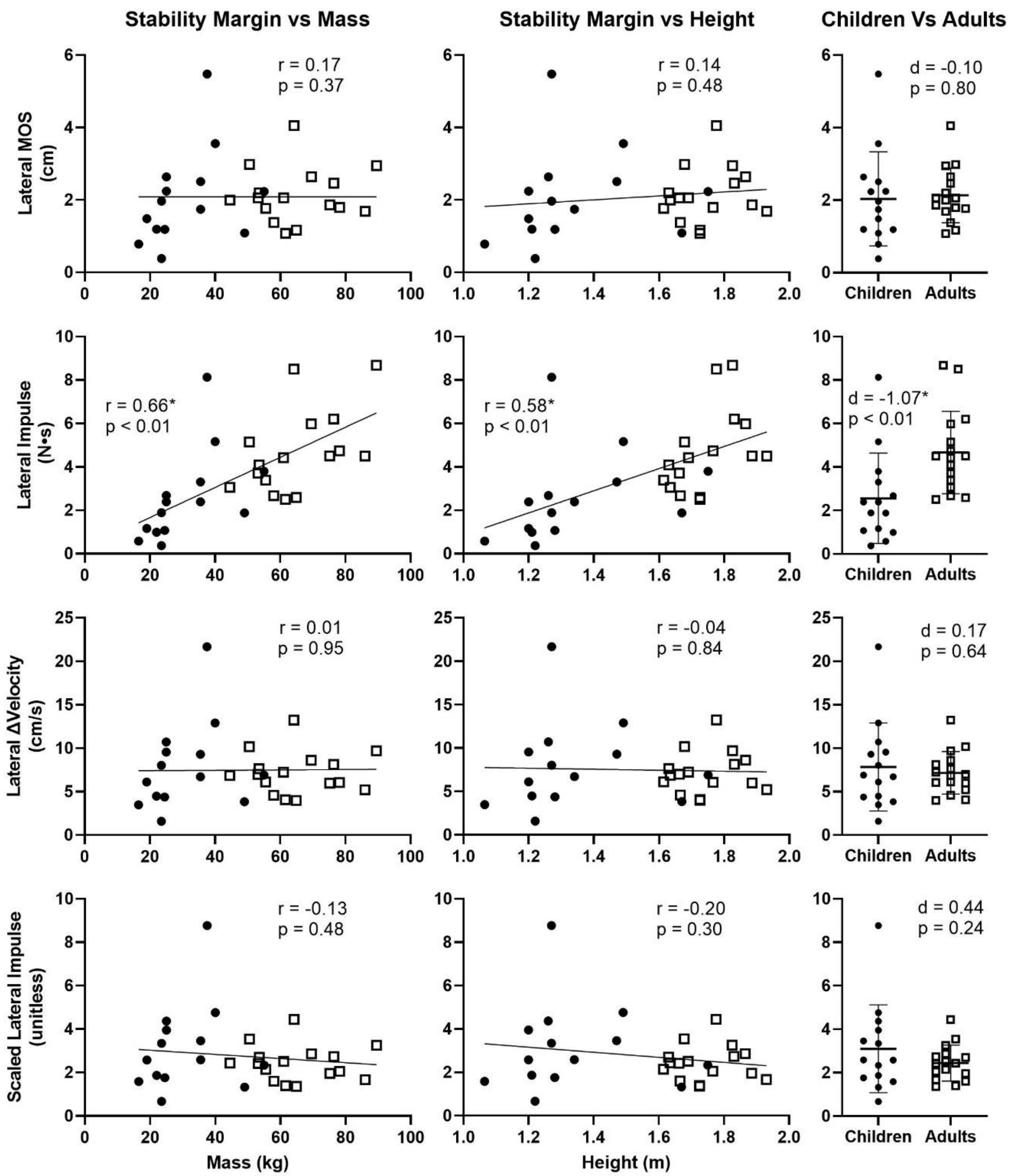

Figure 2: Lateral minimum stability margin expressions correlated with mass (left column), correlated with height (middle column), and compared between children and adults (right column). Closed circles represent typically developing children and open squares represent neurotypical young adults. Pearson r and Cohen d values that are statistically significant are denoted with an asterisk.