The Effect of Arm Restriction on Dynamic Stability and Upper Body Responses to Lateral Loss of Balance During Walking: An Observational Study

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Abstract

Background: When losing balance, arm movements serve as a mechanical aid to regain stability. However, it remains unclear how arm movements contribute to dynamic stability during recovery from a lateral loss of balance while walking. Our objectives were to 1) quantify the effect of arm restriction on gait stability and upper body velocities; 2) test the association between gait stability and upper body velocities; 3) analyze upper body kinematics and strategies in response to lateral surface translations under different arm-restriction conditions.

Methods: Fourteen young adults (age 35±2.3; 7 female) experienced unexpected lateral surface translations while walking on a computerized treadmill under three conditions: 'free arms', '1-arm restricted' and, '2-arms restricted'. Full-body kinematic data were used to extract dynamic stability parameters (measured as the margin of stability in the mediolateral (MoS_ML) and anterior-posterior (MoS_AP) directions), and velocity profiles of the head, trunk and shoulders (measured as the area under the curve) for the first step after perturbation onset. Mixed-effect models were used to test our hypotheses.

Results: A significant main effect for the 'arm restriction condition' indicated lower MoS_AP and higher trunk velocity in the '2-arm restricted' condition compared to the 'free arms' condition. MoS_AP was positively correlated with head velocity and negatively correlated with trunk and shoulder velocities. Additionally, head and trunk movements in the mediolateral (ML) plane were either 'coupled' (i.e., their velocities were in the same direction, 55.69% of responses) or 'decoupled' (i.e., their velocities were in opposite directions, 44.31% of responses). Furthermore, head and trunk velocities were greater in the ML direction compared to the anterior-posterior (AP) direction.

Conclusions: Increased upper body velocities contribute to balance responses following lateral perturbations while walking with arm constraints. The greater the arm constraint, the more pronounced the effect on dynamic stability in the AP direction and upper body velocities. The 2-arm restricted condition may be utilized as a method for targeted perturbation-based balance training, focusing on head and trunk responses during walking.

Key words: falls, balance perturbations, walking, arm constraint, dynamic stability, perturbation-based balance training, fall prevention.

Background

Reactive recovery responses are critical for maintaining dynamic stability following a sudden loss of balance. While extensive research has delved into understanding lower limb reactions to balance disruptions[1–5], the contribution of upper body responses in restoring balance are not fully understood. Increasing the understanding of upper body responses to balance perturbations is vital for identifying rehabilitation training targets for fall prevention.

Previous studies have shown that rapid upper extremity movements are coordinated with lower extremity reactions during balance perturbations while standing and walking[6,7]. These responses have been characterized as a protective strategy against injury, such as positioning the upper extremities to absorb impact energy with the ground or as a recovery strategy to stabilize the body by either reach-to-grasp or assist in counter balancing and decelerating the falling center of mass[8–10] . A recent systematic review[11] highlighted differences in upper extremity responses to different perturbation types between young and older adults. Among these differences are delayed muscle activation onsets and movement onset times during reactive responses in older adults compared to young adults. Also, directional differences in upper extremity responses were demonstrated: older adults tended to move their arms in the same direction as perturbation while young adults tended to move their arms opposite to the direction of perturbation. These directional differences suggest an attempt to arrest the fall at impact in older adults (i.e., to brace against impact) and an attempt to restore an upright position by decreasing fall directed center of mass displacement in young adults (i.e., to restore balance and prevent a fall)[12,13]. Other studies focusing on slips reported bilateral arm flexion to counter the backwards loss of balance[14] and reduce trunk extension velocity which aids in regaining balance[15]. Specifically,

abduction of the arm contralateral to the slipping foot was found to be significantly greater than the sagittal plane movement of the arm in those who successfully recovered from an unexpected slip[16]. While most studies have focused on slips that induce a backward loss of balance[15–18] or trips[12,19] that induce a forward loss of balance, losses of balance in real world can be induced in all directions.

To date, limited data exist regarding upper body responses to lateral perturbations during walking. Additionally, the impact of constraining the upper extremity movements on dynamic stability and upper body reactive strategies has not been experimentally tested. This is particularly important as daily tasks or orthopedic/neurological conditions may restrict upper extremity responses. A previous study that employed an arm constraint approach to investigate upper body responses to slips in young adults demonstrated a significantly higher rate of falls when both arms were restricted[16]. It was suggested that the increased fall frequency in the arm restricted condition resulted from the inability to initiate an effective alternative strategy to control center of mass excursion and recover balance. However, this study did not assess the strategies used to recover balance and body kinematics, limiting our understanding of the underlaying mechanisms.

The objectives of the current study were threefold: 1) to quantify the effect of arm restriction on dynamic stability and upper body kinematics in response to lateral surface translations during gait; 2) to test the association between gait stability and upper body kinematics in response to lateral surface translations under different arm-constraints; and 3) to characterize upper body kinematics and strategies in response to lateral surface translations under different arm-constraints. We hypothesized that 1) greater arm constraint will lead to decreased dynamic stability and increased upper body segment velocities compensating for restricted arm movement; 2) dynamic stability and upper

body velocities would both increase to counteract the initial perturbation velocity. Since participants experienced lateral perturbations, inducing a mediolateral velocity, we hypothesized that positive correlations between dynamic stability and upper body velocities in the frontal plane and negative correlations between dynamic stability and upper body velocities in the sagittal plane will be observed; and 3) upper body velocities will be most prominent in the mediolateral direction to counteract the initial velocity in the loss of balance direction.

Methods

Participants

Fourteen healthy young adults (7 females; aged 35±2.3 years) participated in the study. Participants were included if they were aged between 20-40, and without any neurological, vestibular, or orthopedic conditions that may affect their balance and/or gait. All participants signed an informed consent form prior to participating in the study. The study was approved by the institution review board at Loewenstein Rehabilitation Medical Center (LRMC) (approval number LOE-14-0021).

Procedure

All assessments were conducted at the Locomotor Recovery Laboratory in LRMC. Participants walked on a computerized treadmill system with a horizontal movable platform (Balance Tutor, MediTouch LTD, Tnuvot, Israel) at their preferred walking speed determined from the average of two overground 10-meter walk tests. Participants walked under three conditions, each lasting 120 seconds in the following order: 1) unrestricted any upper body movement, ‘free arms’ condition; 2) the dominant arm restricted with a sling, ‘1-arm restricted’ condition; 3) both arms restricted with slings, ‘2-arm restricted’ condition (Figure 1). In each condition the participants were subjected to four (2 rightward and 2 leftward) lateral surface translations (platform

displacement of 12 cm, velocity of 42 cm/sec and acceleration of 145 cm/sec^2). Participants were not informed regarding the timing or direction of perturbations. The surface translations were induced in the following order: rightward, leftward, leftward, and rightward. The time interval between perturbations was random (between 30-45 seconds) to reduce perturbation onset prediction. Participants were asked to react naturally to prevent falling during surface translations.

[Insert Figure 1 about here]

Kinematic data collection and analyses

A total of 34 reflective markers were strategically placed on anatomical landmarks in accordance with the Plug-In-Gait marker set (full body Plug in Gait model, Vicon Motion Systems, Oxford, UK). Three additional markers were affixed to the platform to synchronize platform movement data with kinematic data. Eight Vicon infrared motion capture cameras (Vicon Motion System, Oxford, UK) recorded kinematic data from the head, trunk, lower limbs, and upper limbs at a sampling rate of 120 Hz. The data were low-pass filtered using a zero-lag, fourth-order Butterworth filter with a cut-off frequency of 15 Hz. Prior to analysis, motion data were preprocessed and analyzed using Vicon Nexus software (Version 2.0) and checked for marker trajectory disruptions.

Gait events and parameters were computed using custom MATLAB scripts (version R2022b, MathWorks, Natick USA). Preprocessed data were used to identify the initial contact, defined as the local maxima of the heel marker position in the anterior-posterior (AP) direction. To assess the dynamic stability, the Margin of stability (MoS) in the anterior-posterior (AP) and mediolateral (ML) directions were calculated using the formula (based on[20]:

(Eq.1)

$$XcoM = PCoM + \left(VCoM / \sqrt{(\frac{g}{l})}\right)$$

Where $XcoM$ is the extrapolated center of mass, P_{CoM} is the AP or ML component of the projection of the center of mass on the ground. V_{CoM} is the CoM-velocity in the respective direction. The term √(g/l) presents the eigen frequency of an inverted pendulum system with a leg of length l.

(Eq.2)

$$MoS = Umax - XcoM$$

Where MoS_x specifies the MoS in the AP or ML direction (from herein the term **MoS_AP** and **MoS_ML** will be used), Umax is the anterior or lateral boundary of the base of support (BoS) and the XcoM is the position of the XcoM in the relevant direction.

To compute the velocity of the head, trunk, and shoulders, we first determined their positions. The head position was determined as the average of the four head markers in 3D space. Trunk position was determined as the average position of the sternum, C7 and T10 markers. The first derivative of the preprocessed marker position was calculated to obtain velocity. Head, trunk, and shoulders' velocity vectors were interpolated to 101 samples (to normalize step after perturbation to 100%) whose absolute values (aims 1 and 2) or true values (aim 3) were used to calculate the area under the curve (AUC). These were calculated to obtain the velocity magnitude in the balance response (aims 1 and 2) and the dominant velocity direction (aim 3), respectively.

Furthermore, to highlight the dominant direction of the upper body velocities in response to perturbation we have separated the ML and AP planes (aim 3). Also, we described the direction of the upper body velocity in relation to the direction of the induced loss of balance, such that velocities were increased in the direction of the loss of balance or in the opposite direction to the loss of balance (e.g., right surface translation induces a leftward loss of balance. If upper body velocity in response to perturbation was towards the left, it was characterized as velocity in the direction of the induced loss of balance). All outcome measures were calculated for the first step after perturbation onset. Trials in which the step after the perturbation was shorter than 10 kinematic data points were discarded (see Table S1 in *supplementary materials* for summary of the discarded trials). Perturbation direction was defined based on whether the surface translation was towards the participant's dominant or non-dominant side and the shoulders were defined as the dominant or non-dominant shoulder.

Statistical analysis

Dependent variables comprised: MoS_AP, MoS_ML, and the area under the curve (AUC) of head, trunk and shoulder velocities. Normality of variable distributions was assessed using distribution plots and the Shapiro-Wilks test on model residuals. Outliers were examined with the 'check_outliers' function using "Z-scores," "ci," and "iqr" methods, identifying possible outliers for each outcome variable (see Table S2 and Table S3 in the supplementary materials). As outliers did not affect the models, all samples were retained, and potential outliers were not removed. For aim 1, examining the effect of the 'arm restriction condition' on dynamic stability and upper body velocities, Z-scores were standardized to ensure scaled coefficients across models. Then, we calculated six mixed-effect models, each representing one outcome variable, with 'participants' as the *random* effect. Within-subject variables included: 'arm

restriction condition', 'perturbation direction' (surface translation toward the dominant vs. non-dominant side), 'stance limb' (dominant vs. non-dominant limb), and the interactions: 'arm restriction condition' X 'perturbation direction' and 'arm restriction condition' X 'stance limb'. Post-hoc analysis was conducted with Holm's (sequential Bonferroni) method correction for multiple comparisons.

For aim 2, testing association between dynamic stability and upper body velocities, two mixed-effect models (one for each plane, AP or ML) with 'participants' as the *random* effect were developed. Within-subject variables included: head, trunk, and shoulder velocities, along with condition.

For aim 3, characterizing upper body kinematics in response to lateral surface translations under various arm-constraints, four mixed-effect models (one for each segment: head, trunk, and shoulders) were established, again with 'participants' as the random effect. Within-subject variables included: 'plane' (AP vs. ML), 'arm restriction condition' and 'upper body strategies' (i.e., velocity in the direction or opposite direction of the loss of balance induced by the perturbation). Post-hoc analysis with Holm's (sequential Bonferroni) method correction for multiple comparisons was carried out.

All statistical analyses were performed using the 'lme4' package in R version 4.2.2.

Results

Participants

Participants' characteristics are summarized in Table 1. The dependent variables of the full dataset, arranged by participant, are summarized in Table S2, in the *supplementary material*. The initial dataset included 138 trials. However, eight observations were excluded due to having less than 10 data points of kinematic data. Therefore, the final

analysis included 130 observations of which 48 were in the ‘free arms’, 40 in the ‘1-arm restricted’ and 42 in the ‘2-arm restricted’ conditions.

Table 1. Participants’ characteristics

Participant	Sex	Age (years)	Height (cm)	Weight (kg)	BMI	Walking speed (km/h)	Dominant side
01	F	35	1.62	57.2	21.79	5.2	R
02	M	36	1.74	77.1	25.46	5.1	R
03	M	37	1.86	76	21.96	5.7	R
04	F	34	1.64	75.7	28.14	5.2	R
05	F	38	1.68	57.5	20.37	4.8	R
06	M	39	1.78	78.6	24.8	4.6	L
07	F	37	1.64	55.2	20.52	4.4	R
08	M	34	1.84	92	27.17	6.4	R
09	F	35	1.75	78	25.46	4.3	L
10	M	33	1.82	72.7	21.94	4.6	L
11	F	34	1.62	72	27.43	4.3	R
12	M	33	1.74	82.7	27.31	5.4	R
13	F	38	1.66	55.6	20.17	4.6	R
14	M	31	1.71	67.6	23.11	3.6	R

Abbreviations: M-male, F-Female; R-right, L-Left; BMI – body mass index

Effect of arm restriction on gait stability and upper body velocities

Significant main effects of the ‘arm restriction condition’ were observed for MoS_AP and trunk velocity. Notably, the 'free arms' condition exhibited significantly higher MoS_AP compared to the ‘1-arm restricted’ condition ($p=0.007$, Table 2). Conversely, trunk velocity was significantly higher in both the ‘1-arm’ and’2-arms restricted’ conditions in comparison to ‘free arms’ condition ($p=0.007$ and $p=0.047$, respectively, Table 2).

A significant interaction between ‘arm restriction condition’ and ‘perturbation direction’ indicated that when the surface translation occurred toward the non-dominant side, the ‘2-arms restricted’ condition exhibited higher head and shoulders velocities than the ‘free arms’ condition ($p\leq0.002$, Table 2). On the other hand, significant ‘arm

restriction condition' X 'stance limb' interaction effects revealed that when the non-dominant limb led the reactive response, lower head and shoulder velocities were observed in the '2-arms restricted' condition compared to the 'free arms' condition ($p \leq 0.004$, Table 2).

Table 2: Mixed effects model summaries for restricted condition effect on dynamic stability and upper body velocities.

MoS ML			
Predictors	*Estimates*	*CI*	*p*
(Intercept)	-0.12	-0.56 – 0.33	0.597
1-Arm restricted	0.32	-0.23 – 0.87	0.248
2-arms restricted	-0.28	-0.85 – 0.29	0.337
stance limb [Non-dominant]	1.29	-0.63 – 3.22	0.186
Perturbation direction [Non-dominant]	-1.21	-3.12 – 0.71	0.216
1-Arm restricted * stance limb [Non-dominant]	0.01	-0.78 – 0.80	0.985
2-Arms restricted * stance limb [Non-dominant]	-1.20	-3.93 – 1.54	0.387
2-Arms restricted * Perturbation direction [Non-dominant]	1.55	-1.18 – 4.27	0.263
Marginal R^2 / Conditional R^2	0.061 / 0.200		
MoS AP			
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.34	-0.12 – 0.80	0.142
1-Arm restricted	-0.61	-1.06 – -0.17	**0.007**
2-arms restricted	-0.41	-0.87 – 0.05	0.081
stance limb [Non-dominant]	0.53	-1.03 – 2.09	0.504
Perturbation direction [Non-dominant]	-0.48	-2.03 – 1.07	0.540
1-Arm restricted * stance limb [Non-dominant]	0.55	-0.08 – 1.18	0.087

2-Arms restricted * stance limb [Non-dominant]	-1.83	-4.05 – 0.39	0.106
2-Arms restricted * Perturbation direction [Non-dominant]	1.45	-0.76 – 3.65	0.197
Marginal R^2 / Conditional R^2	0.110 / 0.471		

Head velocity

Predictors	*Estimates*	*CI*	*p*
(Intercept)	-0.04	-0.50 – 0.43	0.872
1-Arm restricted	0.13	-0.32 – 0.57	0.569
2-arms restricted	-0.38	-0.84 – 0.08	0.103
stance limb [Non-dominant]	-0.67	-2.24 – 0.89	0.395
Perturbation direction [Non-dominant]	0.62	-0.93 – 2.17	0.429
1-Arm restricted * stance limb [Non-dominant]	-0.04	-0.67 – 0.59	0.904
2-Arms restricted * stance limb [Non-dominant]	4.21	1.99 – 6.43	**<0.001**
2-Arms restricted * Perturbation direction [Non-dominant]	-3.75	-5.96 – -1.55	**0.001**
Marginal R^2 / Conditional R^2	0.101 / 0.481		

Trunk velocity

Predictors	*Estimates*	*CI*	*p*
(Intercept)	-0.51	-0.98 – -0.03	**0.036**
1-Arm restricted	0.61	0.17 – 1.06	**0.007**
2-arms restricted	0.47	0.01 – 0.93	**0.047**
stance limb [Non-dominant]	0.59	-0.97 – 2.15	0.454
Perturbation direction [Non-dominant]	-0.19	-1.74 – 1.36	0.808
1-Arm restricted * stance limb [Non-dominant]	-0.62	-1.26 – 0.01	0.053

2-Arms restricted * stance limb [Non-dominant]	1.33	-0.90 – 3.55	0.240
2-Arms restricted * Perturbation direction [Non-dominant]	-1.37	-3.58 – 0.84	0.222
Marginal R^2 / Conditional R^2	0.089 / 0.487		

Dominant shoulder velocity

Predictors	*Estimates*	*CI*	*p*
(Intercept)	-0.20	-0.67 – 0.28	0.413
1-Arm restricted	-0.02	-0.49 – 0.44	0.928
2-arms restricted	0.27	-0.21 – 0.75	0.266
stance limb [Non-dominant]	-0.52	-2.15 – 1.12	0.534
Perturbation direction [Non-dominant]	0.73	-0.89 – 2.36	0.374
1-Arm restricted * stance limb [Non-dominant]	-0.19	-0.85 – 0.48	0.575
2-Arms restricted * stance limb [Non-dominant]	3.46	1.13 – 5.79	**0.004**
2-Arms restricted * Perturbation direction [Non-dominant]	-3.65	-5.96 – -1.33	**0.002**
Marginal R^2 / Conditional R^2	0.087 / 0.443		

Non-dominant shoulder velocity

Predictors	*Estimates*	*CI*	*p*
(Intercept)	-0.08	-0.51 – 0.35	0.717
1-Arm restricted	0.11	-0.28 – 0.50	0.570
2-arms restricted	-0.16	-0.56 – 0.24	0.429
stance limb [Non-dominant]	-1.21	-2.57 – 0.15	0.080
Perturbation direction [Non-dominant]	1.19	-0.16 – 2.54	0.085
1-Arm restricted * stance limb [Non-dominant]	-0.07	-0.62 – 0.48	0.802

2-Arms restricted * stance limb [Non-dominant]	7.10	5.16 – 9.03	**<0.001**
2-Arms restricted * Perturbation direction [Non-dominant]	-6.90	-8.82 – -4.97	**<0.001**
Marginal R^2 / Conditional R^2	0.252 / 0.611		

Abbreviations: CI = 95% confidence interval, p = p value

Associations between dynamic stability parameters and upper body velocities

A positive correlation between MoS_AP and head velocity was observed such that for every unit increase in head velocity, MoS_AP was increased by 1.28 (p=0.013, Figure 2). A negative correlation between MoS_AP and trunk, and shoulders (dominant and non-dominant shoulders) velocities was observed in the 2-arm restricted condition such that for every unit decrease in MoS_AP, was compensated with increases by 0.67, 0.84, 0.73 and 0.73, respectively (p≤0.039, Figure 2). The model for MoS_ML was not significant (P=0.099).

[Insert Figure 2 about here]

Upper body strategies

The movement of the head and trunk in the mediolateral plane was either 'coupled' (i.e., the velocity of both the head and trunk was in the same direction, 36.15% of responses, Figure 3A-B) or 'decoupled' (i.e., the velocity of the head and trunk was in opposite directions, 63.85% of responses, Figure 3C-D). In the 'coupled' strategy, the upper body velocities were either in the same direction as the direction of loss of balance (16.15% of responses, Figure 3A) or in the opposite direction to the loss of balance (20% of responses, Figure 3B). For the 'decoupled' strategy, in 37.69% of the responses the head's velocity was in the opposite direction to the loss of balance while the trunk velocity was in the same direction as the loss of balance (Figure 3C). In

26.15% of the responses the velocity of the trunk was in the opposite direction to the loss of balance while the velocity of the head was in the same direction as the loss of balance (Figure 3D).

[Insert Figure 3 about here]

Upper body kinematics

The models for the head, trunk, and non-dominant shoulder showed significant main effects for 'plane' (AP vs. ML) ($F_{[1,255]}$=104.31, p<0.001; $F_{[1,255]}$=19.99, p<0.001; and $F_{[1,255]}$=5.04, p=0.026, respectively). Head and trunk had significantly greater velocities in the ML vs. AP plane (t=8.76, p<0.001 and t=4.18, p<0.001, respectively). The non-dominant shoulder had significantly greater velocities in the AP vs. ML plane (t=2.04, p=0.04).

Significant main effects of 'upper body strategies' were found for the trunk and non-dominant shoulder $F_{[1,255]}$=29.23, p<0.001 and $F_{[1,255]}$=5.41, p=0.021, respectively), indicating increased velocities in the opposite direction of the loss of balance (t=5.05, p<0.001 and t=2.10, p=0.036, respectively), Figure 4.

[Insert Fig. 4 about here]

Discussion

In this study, we aimed to examine the effect of different arm constraints on dynamic stability and upper body velocities in response to lateral surface translations and the associations between dynamic stability and upper body velocities under these conditions. We found that 1) restricting the movements of the arms led to increased

head, trunk and shoulders velocities in comparison to ‘free arms’ condition, supporting our hypothesis that greater arm constraint will lead to increased upper body velocities; and 2) restricting the arms affected dynamic stability in the AP direction as was shown by reduced MoS_AP in comparison to ‘free arm’ condition. Also, significant associations between dynamic stability measures of MoS_AP and upper body velocities were found, partially supporting our hypotheses that MoS_ML and MoS_AP will be correlated with upper body velocities. These results, together with the observations of increased shoulder velocities in the AP direction and increased head and trunk velocities in ML direction, partially support our hypothesis that upper body velocities will be greater in the ML direction compared with the AP direction to counteract the loss of balance.

Effect of arm restriction on dynamic stability and upper body velocities

Our results regarding the effect of arm restriction on dynamic stability and upper body velocities in response to lateral surface translations during walking are consistent with previous literature showing a significant effect of arm restriction on dynamic stability in response to balance perturbations during walking[21,22] and standing[23]. A previous study showed that higher incidence of falls in response to a slip were observed in ‘arms restricted’ condition compared with ‘free arms’ condition[21]. In another study reduced gait stability was demonstrated in a condition where the arm swing was restricted[22]. It is of importance to note that in these studies both arms were restricted. This finding was supported by our findings of significant effect of 2-arm restriction condition but not in the 1-arm restricted condition. Our finding that the effect of arm restriction on dynamic stability was significant only in the ‘2-arm restricted’ condition but not in the ‘1-arm restricted’ condition suggests that young healthy adults can successfully compensate for not being able to react with one arm. However, in case of

a substantial arm restriction (i.e., 2 arms), even young healthy adults need to change their response and react by increasing head, trunk and shoulder velocities. This was supported by our finding of significant main effects and interactions. This raises the question whether older healthy adults or people with neurological disorders will demonstrate a lower "constraint threshold" to evoke a compensatory response of increased head, trunk and shoulder velocities. Further research is needed to answer these questions. Furthermore, the trend of increased velocities with increased difficulty level suggests that arm restriction could be used as a methodology to focus perturbation-based balance training on head and trunk responses during walking.

Associations between dynamic stability parameters and upper body velocities

To the best of our knowledge, the relationship between dynamic stability and upper body velocities, in conjunction with arm movement restriction in response to lateral surface translations was not discussed in previous literature. Our findings of a significant relationship between dynamic stability and upper body velocities are in line with previous findings[24], demonstrating significant correlations between dynamic stability and trunk velocity in response to perturbations while standing (in [24] no arm restriction was applied). Nevertheless, in the current study, this relationship between upper body velocities and dynamic stability was significant in the AP plane, but not in the ML plane. This, together with low- moderate R^2 values (Table 2), suggests that the upper body velocities are not the only compensation mechanisms to the loss of balance induced in the ML direction and reduced stability in AP direction. This assumption is supported by previous findings, showing a strong relationship between the length of the first recovery step and stability measures[24]. Further research is required to test if this mechanism also applies to lateral perturbations during walking as well.

Upper body kinematics and strategies

Our results showed that the head and trunk velocities were significantly greater in the ML direction compared to the AP direction when controlling for the 'arm restriction condition' and 'upper body strategy'. Additionally, trunk and non-dominant shoulder velocity were associated with upper body strategy demonstrating higher velocity in the direction opposite to the direction of loss of balance vs. the same direction as loss of balance.

The findings of two distinct upper body strategies in response to lateral perturbations, namely in the same direction or in the opposite direction to the loss of balance direction are in line with previous literature[11]. While previous studies demonstrated arms velocities in the direction of the loss of balance in older adults, we show for the first time this behavior in young adults in the context of head and trunk kinematics. We assume that in young adults this behavior of responding with the head and trunk in the same direction as the loss of balance without falling is made possible by compensation of other balance response mechanisms such as arm movements and stepping responses. Nevertheless, testing this assumption requires further study.

Limitations

Several methodological constraints should be acknowledged. First, the timing of perturbations relative to the gait cycle phase could not be controlled for, thus perturbations were introduced in different phases during the gait cycle. However, we were interested in the upper body velocities during the first step after perturbation and the MoS at the time of the initial contact which may be less affected by this limitation. Also, we made sure that we had at least 10 data points after the perturbation which assured lower variation of the perturbation onset in relation to the gait cycle.

Second, the arm restriction conditions were introduced in the same order between participants, with no randomization which potentially caused fatigue in the constrained conditions. One would expect to find reduced upper body velocities if fatigue was introduced, however, we did not observe that in the results. On the other hand, one may argue that fatigue may affect lower limb responses, leading to increased upper body velocities for compensation. However, in this case we should have observed negative correlations between the MoS_ML and the upper body velocities (i.e., reduced MoS would associate with increased upper body velocities) but this was not demonstrated.

Finally, our study was based on healthy young adults and thus our findings cannot be generalized to other populations such as older adults and people with movement disorders. Learning about the compensatory strategies in these populations requires a separate investigation.

Conclusions

Our findings highlight the pivotal role of increased upper body velocities as a compensatory mechanism for maintaining balance control in response to lateral surface translations during walking with arm constraints. In the current study, we observed a graded effect of arm restriction, wherein greater arm restriction leads to increased upper body velocities. Importantly, our observations challenge the assumption that upper body velocities invariably oppose the direction of balance loss. Additionally, Moderate correlations between MoS and upper body velocities, along with head and trunk coupled velocities in the direction of balance loss suggest that while increased upper body velocity is employed to maintain balance, there may be other mechanisms involved. The interplay between the different mechanisms requires further research.

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Figures' captions

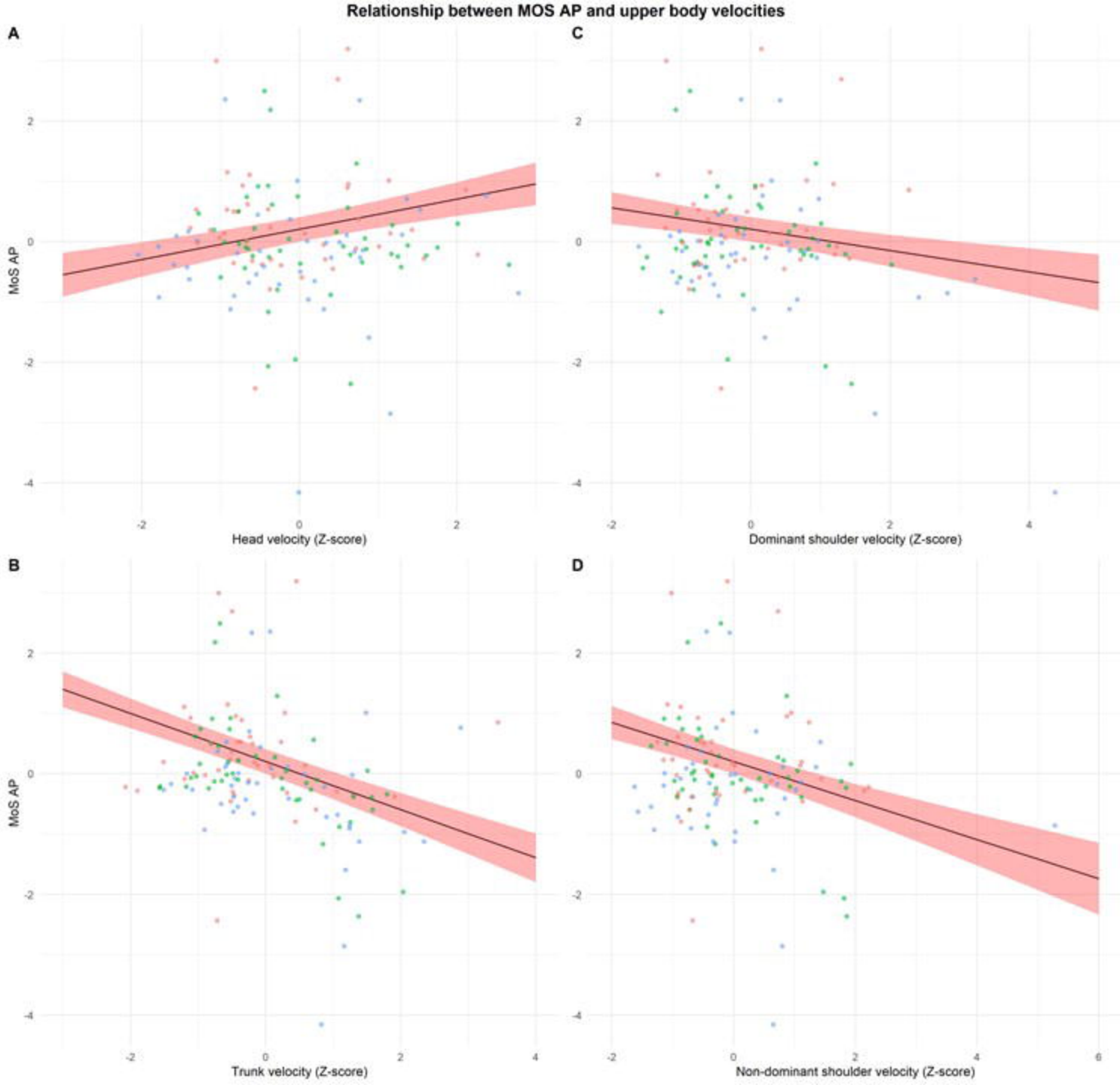
Figure 1. Experimental setup.

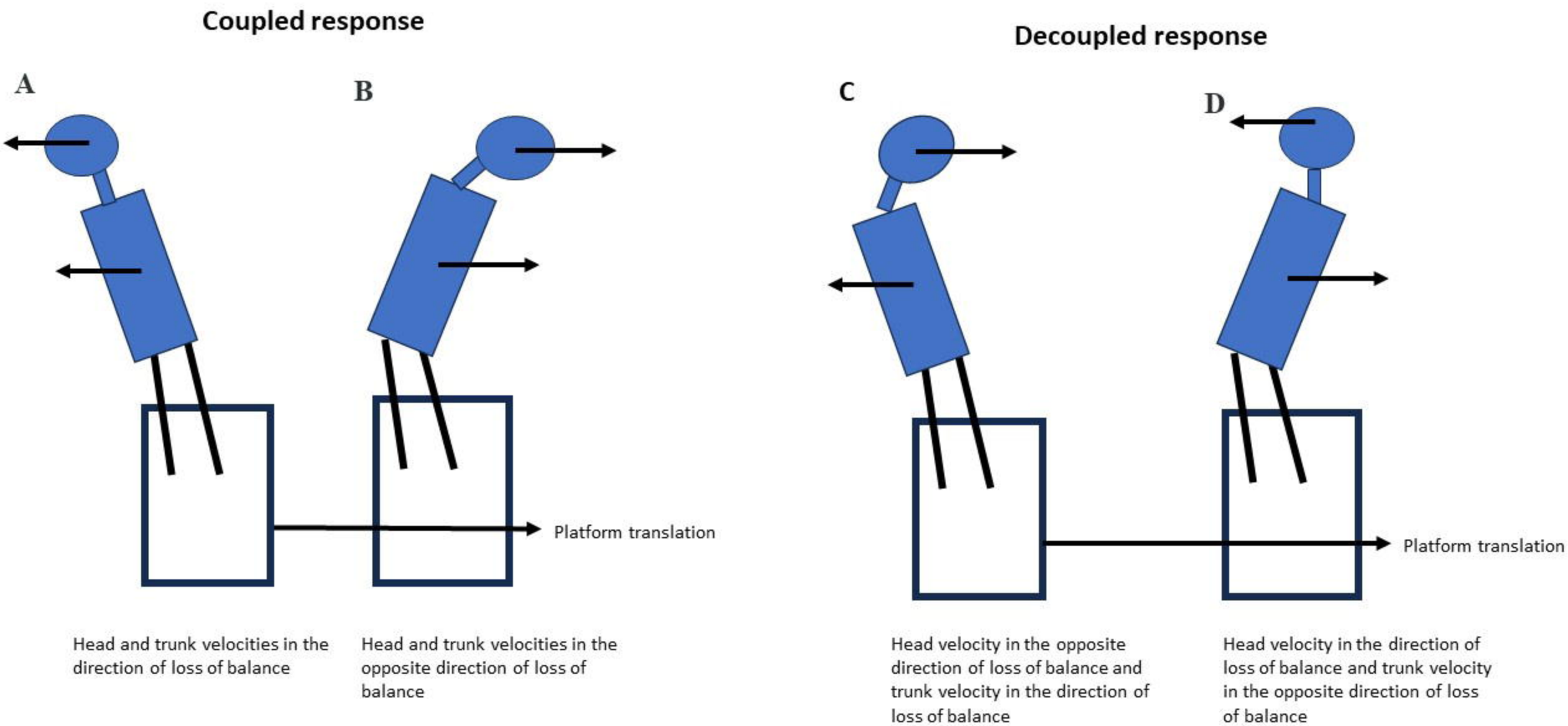
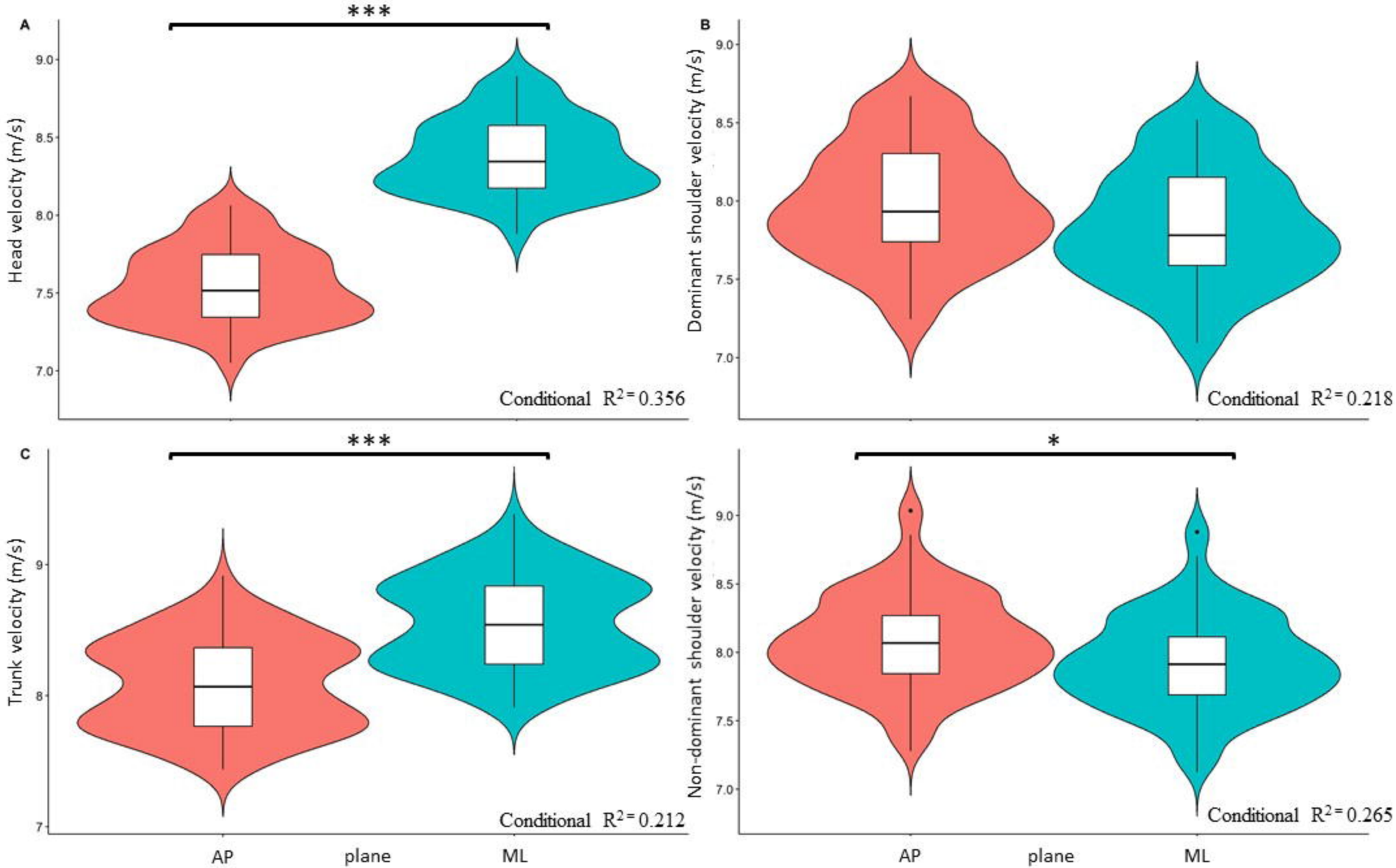
Figure 2: The relationship between dynamic balance and upper body velocities (A-D) in the different arm restriction conditions (red dots – 'free arms', green dots – '1-arm restricted' and blue dots – '2-arms restricted'. Solid black line represents the regression line and shaded area around it the 95% confidence interval. Abbreviations: MoS, margin of stability; ML, mediolateral; AP, anterior-posterior.

Figure 3: Upper body strategies in response to lateral surface translations during walking.

Figure 4: Comparisons between upper body velocities of the head (A), trunk (C), dominant shoulder (B) and non-dominant shoulder (D) in anterior-posterior (AP) vs. mediolateral (ML) planes. *P<0.05, **p<0.01, ***p<0.001.

Free arms
1-arm restricted
2-arms restricted


Relationship between MOS AP and upper body velocities
A
B
C
D
MoS AP
Head velocity (Z-score)
Trunk velocity (Z-score)
Dominant shoulder velocity (Z-score)
Non-dominant shoulder velocity (Z-score)


Coupled response
A
B
Platform translation
Head and trunk velocities in the direction of loss of balance
Head and trunk velocities in the opposite direction of loss of balance
Decoupled response
C
D
Platform translation
Head velocity in the opposite direction of loss of balance and trunk velocity in the direction of loss of balance
Head velocity in the direction of loss of balance and trunk velocity in the opposite direction of loss of balance

Upper body velocity in AP vs. ML Plane