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Angular momentum generation and control during a back handspring step out on the balance beam performed by female gymnasts

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ABSTRACT

The back handspring step out (BHS) is a foundational skill in gymnastics balance beam routines that requires the generation of significant sagittal plane angular momentum while tightly regulating frontal plane momentum to control their balance. However, which body segments are critical for generating this momentum and successfully performing the BHS and whether skill level influences this generation remains unknown. Twenty-five gymnasts with a range of skill levels performed a BHS on a balance beam. The BHS was scored, and segmental contributions to whole-body angular momentum were analyzed during the take-off, flight, hand contact and landing phases. Angular momentum has previously been used to assess balance control, where higher ranges of frontal plane angular momentum are indicative of poorer balance control. There were no differences in segmental contributions to angular momentum during the take-off phase between high- and low-scoring groups. However, the low-scoring group had higher trunk contributions to frontal plane angular momentum after the take-off phase. The trailing leg was also found to be a large contributor to frontal plane angular momentum, and thus more likely than the leading leg to cause deviations in balance control. In the sagittal plane, momentum generation and skill level were weakly correlated, suggesting as gymnasts become more skilled, they produce larger sagittal plane motions and are more adept at generating angular momentum. Because the trunk and trailing leg had high contributions to frontal plane angular momentum, controlling the trunk and trailing leg should be a focus in training regimes to improve BHS performance.

1. Introduction

Although gymnastics is an increasingly popular sport, little research has been performed to understand the mechanics involved in its skilled tasks (Farana et al., 2023). The back handspring step out (BHS) (Fig. 1) is a foundational skill in women's balance beam routines starting at 10 years old through the Olympic level (Fédération Internationale de Gymnastique, 2022). Some studies have investigated a two-footed BHS on the floor and found unique biomechanical demands, such as high valgus moments at the elbow, which can cause lateral compression injuries (Koh et al., 1992). However, fewer studies have investigated the biomechanical demands of a BHS when constrained to the narrow balance beam (e.g., Ede et al., 2021; Pimentel et al., 2020; Small and Neptune, 2024). Maintaining balance during motor tasks on the balance beam is challenging due to the small margin of stability (Hof et al., 2005) available on the beam.

Whole-body angular momentum (H) has been used to assess balance control in a variety of locomotor tasks (Neptune and Vistamehr, 2019), where higher ranges of frontal plane H correlate with lower clinical balance scores, which is indicative of poorer balance control (Nott et al., 2014; Vistamehr et al., 2016). Momentum impulses have also been used to describe various flipping and diving maneuvers (e.g., Mathiyakom et al., 2023, 2006). The demands of the BHS (Fig. 1) require gymnasts to generate significant sagittal plane angular momentum while tightly regulating frontal plane momentum to control their balance. H is partially mediated by changing the moment arm between the center of pressure and body center of mass (CoM). Thus, constraining the mediolateral moment arm on a narrow balance beam can limit the ability of the gymnast to regulate H, and therefore deviations of body segment motion could cause the gymnast to lose their balance and fall. However, it is unknown which body segments are most influential in these deviations that can lead to a loss of balance. Furthermore, it remains unknown if gymnasts' age or skill level serve as accurate predictors of angular momentum generation and control in the BHS.

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Previous analyses found anthropometric and range of motion asymmetries in gymnasts (Frutuoso et al., 2016), in part due to the asymmetric nature and loading of specific skills (Exell et al., 2016; Yeadon and Hiley, 2014). These asymmetries can lead to differences in controlling the angular momentum between the leading and trailing legs. Analyses of segmental angular momentum can help determine which body segments have the highest contribution to *H* (Bruijn et al., 2008) and have previously provided insight into how *H* is regulated for both overground (Begue et al., 2021) and beam (Chiovetto et al., 2018) walking. Segmental analyses can also elucidate which segments to focus on during training in order to improve balance control and thus BHS performance.

The purpose of this study was to identify which segments contribute most to angular momentum generation and control during a BHS and assess the relationship between age, skill level, years of gymnastics experience and BHS performance on the balance beam. To assess performance, the BHS was scored and balance control was quantified using frontal plane *H* throughout the task. We hypothesized that low- and high-scoring BHSs would have different segmental contributions to *H* during the four phases of the BHS. We further hypothesized that there would be differences in segmental *H* magnitude and timing between the leading and trailing legs in all four phases of the BHS due to the asymmetry of the skill that could have important implications for BHS performance.

2. Methods

2.1. Data collection

Twenty-five gymnasts were recruited from the local community (Table 1, Appendix A). All gymnasts provided informed written consent to participate in this protocol approved by The University of Texas at Austin Institutional Review Board. When applicable, minor assent and parental or guardian consent was obtained. All gymnasts were free from musculoskeletal and neuromuscular injuries that would affect their BHS performance. Gymnast demographics were recorded including their age, height, mass, leading leg, skill level, years of gymnastics training and years of training a BHS. Skill level was determined by the level (1–10) the gymnast competed in their previous gymnastics season. Three-dimensional full-body kinematic data were collected at 120 Hz using 61 reflective markers with a 12-camera motion capture system (Vicon, Oxford, UK). Three-dimensional ground reaction force (GRF) data were

Table 1
Gymnast demographics (mean ± standard deviation).

Age (years)	16.1 ± 3.9
Height (cm)	154.7 ± 7.3
Mass (kg)	50.2 ± 8.9
Skill Level in Gymnastics (1–10)	8.3 ± 1.2
Years of Gymnastics Training (years)	11.8 ± 3.7
Years of Training a Back Handspring on Beam (years)	5.6 ± 3.0
Leading Leg (Left/Right)	8 Left/17 Right

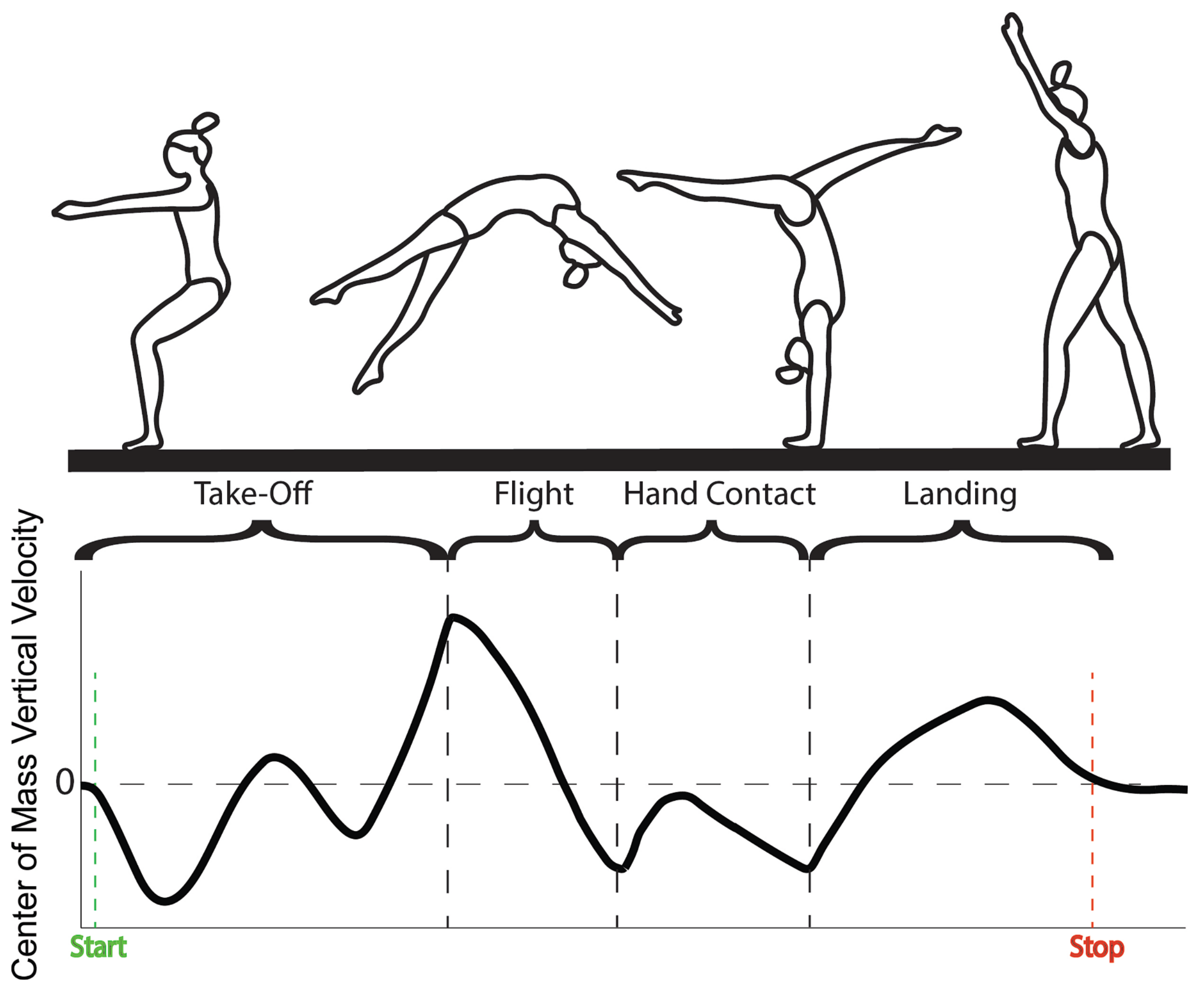

Fig. 1. The back handspring step out and the center of mass velocity throughout the skill.

collected at 960 Hz from six force plates mounted in the ground (Bertec, Ohio, USA). A 2.7 m long and 0.1 m wide floor balance beam made of high density foam (Springee, USA) was placed on top of the force plates. Gymnasts were given as much time as needed to warm up in order to perform the BHS. They then performed three BHSs on the balance beam as if they were in a competition. A trial was repeated if the participant fell off the beam.

2.2. Data processing and analysis

Marker and force plate data were low-pass filtered at 6 Hz and 15 Hz, respectively, using a fourth-order Butterworth filter (Winter, 2009). A 15-segment inverse dynamics model was created for each gymnast using Visual3D (C-Motion, Germantown, MD), including the feet, shanks, thighs, pelvis, thorax, abdomen, upper- and lower-arms and hands. The segment masses were defined in Visual3D based on Dempster's regression equations (Dempster, 1955), while the segments were treated as geometric objects that have inertial properties based on their shape (Hanavan 1964). Dynamic balance was quantified using H, which was calculated by summing the angular momentum of each body segment about the whole-body CoM as:

$$\vec{H} = \sum_{i=1}^{n} [(\vec{r}_i^{\,COM} - \vec{r}_{body}^{\,COM}) \times m_i(\vec{v}_i^{\,COM} - \vec{v}_{body}^{\,COM}) + I_i\vec{\omega_i}] \quad (1)$$

where $\vec{r}_i^{\,COM}$ and $\vec{v}_i^{\,COM}$ are the position and velocity vectors of the i^{th} segment's CoM, respectively. $\vec{r}_{body}^{\,COM}$ and $\vec{v}_{body}^{\,COM}$ are the position and velocity vectors of the whole-body CoM. m_i, I_i, and $\vec{\omega_i}$ are the mass, moment of inertia and angular velocity vector of the i^{th} segment, respectively, and n is the number of body segments. H was normalized by dividing by each gymnast's mass * height^2. The range of H (H_R) was defined as the difference between peaks during the BHS and calculated across the entire BHS in the frontal, sagittal and transverse planes, where lower frontal plane H_R indicates more tightly controlled balance (Herr and Popovic, 2008; Neptune and Vistamehr, 2019). To assess whether H_R is also a reliable measure of balance control in the BHS, we compared frontal plane H_R during the entire BHS to scored performance of the skill, as measured by deductions as outlined in Code of Points (Fédération Internationale de Gymnastique, 2022).

To understand which segments contribute to H, body segment angular momentum was calculated for the arms, legs and trunk as a percentage of the total absolute value of H (i.e., the summation of the absolute value of each segmental angular momenta) (Bruijn et al., 2008) across each of the four BHS phases (Fig. 1), which were defined based on the vertical GRF. Time series differences in segmental angular momentum between the leading and trailing legs were calculated within each BHS phase. The BHS trials started and ended when the magnitude of the CoM velocity > 0 and $= 0$, respectively (Fig. 1). The take-off phase ended when the vertical GRF under the feet $= 0$, the flight phase ended when the vertical GRF under the hands > 0, the hand contact phase ended when the vertical GRF under the first landing foot > 0, and the landing phase ended when the BHS trial ended.

Any trial where the gymnast wobbled such that the BHS included extra steps or large arm swings were excluded since the resulting H would now include balance recovery strategies. The BHS trials were evaluated by a gymnastics expert with over 20 years of gymnastics experience using the Code of Points (Fédération Internationale de Gymnastique, 2022). Deductions were taken on a scale from 0.1 (small errors) to 0.5 (large errors) from 'bent arms or knees,' 'deviation from straight direction,' incorrect 'body and/or leg position' or 'lack of balance,' among other faults (Fédération Internationale de Gymnastique, 2022). Gymnasts were then split into a high-scoring group (deductions < 0.5) and a low-scoring group (deductions ≥ 0.5) based on these deductions. Deductions were used in part to quantify the BHS performance.

2.3. Statistics

To assess differences in segmental H between high-scoring (deductions < 0.5) and low-scoring (deductions ≥ 0.5) BHSs, one-way analysis of variance tests for each plane with a random effect of subject were performed on the average of each gymnast's trials. Tukey-Kramer tests were used to identify differences in average segmental H contributions between the two groups for each of the BHS phases. Statistical parametric mapping (Pataky, 2012) determined differences in segmental H between the leading and trailing legs throughout the BHS phases. Linear regressions were also used across averaged H_R and age, years of participation in gymnastics and skill level for each gymnast to check for covariates. All statistical analyses were performed using the statistical toolbox in MATLAB (Mathworks, Natick, MA). The significance level was set at $p < 0.05$.

3. Results

3.1. Segmental angular momentum during the BHS

When comparing mean percentage segmental contributions to H between the high-scoring (deductions < 0.5, n = 6) and low-scoring (deductions ≥ 0.5, n = 19) groups, there were no differences during the take-off phase (Fig. 2a). During the flight phase, the low-scoring group had higher frontal plane contributions from the legs ($p = 0.047$), and in the transverse plane, the trunk had a higher contribution ($p = 0.002$) and the arms had lower contributions ($p = 0.019$), than the high-scoring group (Fig. 2b). During hand contact, the low-scoring group had a higher frontal plane contribution from the trunk ($p = 0.034$), higher sagittal plane contributions from the arms ($p = 0.020$) and lower sagittal plane contributions from the legs ($p = 0.023$), than the high-scoring group (Fig. 2c). Finally, during the landing phase, the low-scoring group had a higher frontal plane contribution from the trunk ($p < 0.001$) than the high-scoring group (Fig. 2d).

Overall, the trunk and arms were large contributors to H during the take-off phase, while the legs contributed most to H during the flight and hand contact phases (Fig. 2 and Table 2). During the flight and hand contact phases, when the legs were in the air, the leading leg produced a higher percentage of the total H than the trailing leg in the sagittal plane, while the trailing leg had a higher percentage of the total H in the frontal plane (Fig. 3 and Table 2).

3.2. Relationships between demographics and BHS performance

The values for H_R in all three planes can be found in Table 3. A weak but significant correlation existed between the BHS frontal plane H_R and point deductions ($r^2 = 0.233$, $p < 0.001$). In checking for covariates, BHS frontal plane H_R was not correlated with age ($r^2_{BHS} = 0.081$), years of gymnastics training ($r^2_{BHS} = 0.082$) or skill level ($r^2_{BHS} = 0.003$). BHS sagittal plane H_R was not correlated with age ($r^2_{BHS} = 0.044$) or years of gymnastics training ($r^2_{BHS} < 0.001$). Interestingly, BHS sagittal plane H_R increased as skill level increased ($r^2_{BHS} = 0.092$, $p_{BHS} = 0.001$). BHS transverse plane H_R was not correlated with age ($r^2_{BHS} = 0.011$), years of gymnastics training ($r^2_{BHS} = 0.091$) or skill level ($r^2_{BHS} = 0.123$).

4. Discussion

The purpose of this study was to identify which segments contribute most to angular momentum generation and control during a BHS on the balance beam and assess the relationship between age, skill level, years of gymnastics experience and BHS performance. We hypothesized that low-scoring BHSs would have differences in the segmental contributions to H compared to the high-scoring BHSs, and this hypothesis was partially supported after the take-off phase. We also hypothesized that there would be differences in segmental H between the leading and trailing legs in the BHS, which was supported after the take-off phase.

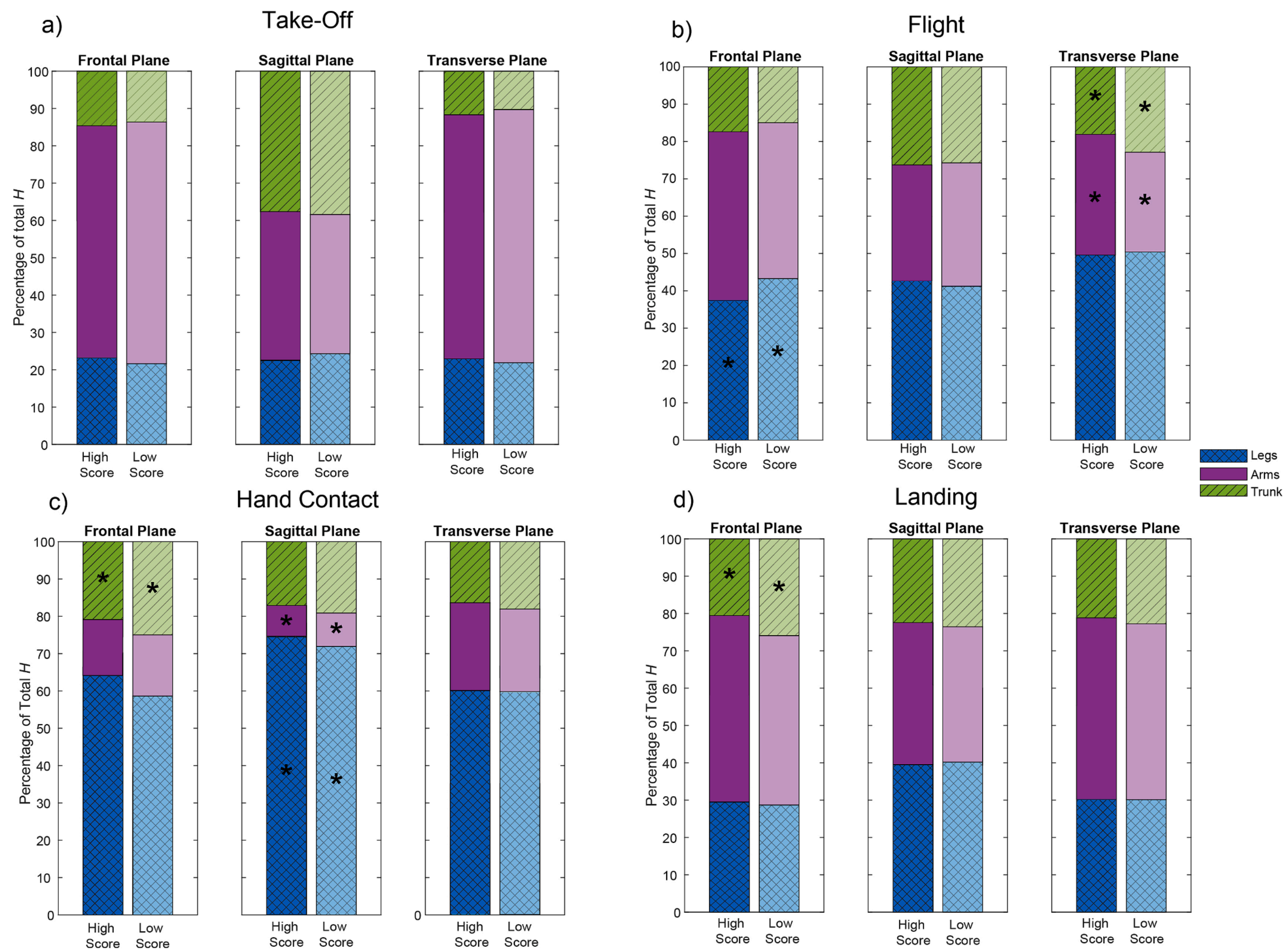

Fig. 2. Average percentage segmental contributions to the total absolute value of whole-body angular momentum (*H*) for the three planes across the back handspring phases: (a) take-off, (b) flight, (c) hand contact and (d) landing. The high-scoring performances are the darker colored columns on the left (deductions < 0.5), and the low-scoring performances are the lighter colored columns on the right (deductions ≥ 0.5). Each pattern represents specific body segments. "*" indicates a significant difference between the high- and low-scoring groups for each group of body segments ($p < 0.05$).

4.1. Segmental angular momentum during the BHS

The segmental angular momentum analysis of the BHS revealed differences in contributions to total angular momentum between high- and low-scoring BHSs that have implications for improving BHS performance. The similarity between the high- and low-scoring groups in the take-off phase is consistent with other research showing near identical take-offs in two variations of a BHS on the balance beam (Ede et al., 2021). After the take-off phase, the low-scoring group had a higher transverse contribution to *H* from the trunk during the flight phase, indicating the trunk begins to twist in flight and alter the gymnast's balance control. Thus, the low-scoring BHSs are likely unevenly activating muscles on the leading and trailing sides that regulate trunk rotation midair (between ~30 and 50 % of the BHS). These results have implications for improving their balance control by maintaining body alignment in the air by engaging both sides of the trunk muscles, with a specific focus after take-off. In addition, future studies should use modeling and simulation to investigate how individual muscles contribute to trunk angular momentum to identify specific muscle groups to focus on.

During the hand contact and landing phases, the trunk contributed more to frontal plane *H* in the low-scoring group than the high-scoring group. The trunk is an important contributor to balance control during walking due to its large mass (Begue et al., 2021; Verheyden et al., 2006), and low-scoring BHSs often have deductions due to unsteady motion or brief periods balance disruptions (Fédération Internationale de Gymnastique, 2022). These results suggest that the trunk is the primary source of these losses of angular momentum control and cause of deductions, even during hand contact when the trunk is closer to the beam. The segmental angular momentum analysis also revealed the importance of the trunk in generating the sagittal plane momentum during take-off necessary to complete the skill. These results further highlight the importance of the trunk in controlling the rotation for the flip and maintaining balance control throughout. Thus, training regimes should emphasize not only maintaining the alignment of the trunk, but also using it for generating needed momentum.

The segmental angular momentum analysis also showed differences between the leading and trailing legs after the take-off (Fig. 3). The BHS on the balance beam is an asymmetrical skill with the legs splitting after take-off (Fédération Internationale de Gymnastique, 2022). The leading leg initially has a higher sagittal plane contribution to generating angular momentum until it begins to lower towards the beam during hand contact and then the trailing leg has a higher contribution (Fig. 3). These results also highlight the importance of maintaining the trailing leg's frontal plane angular momentum as it was significantly higher throughout the majority of the skill (Fig. 3). BHS training routines often focus on the role of the leading leg generating the angular momentum; however, these results suggest also focusing on the positioning of the

Table 2
The average values of the total absolute value of H (1/s) across each of the four phases (mean ± standard deviation), normalized by mass * height^2.

	Plane	Legs	Arms	Trunk
Take-Off	Frontal	0.003 ± 0.001	0.009 ± 0.003	0.002 ± 0.001
	Sagittal	0.012 ± 0.006	0.029 ± 0.020	0.021 ± 0.017
	Transverse	0.003 ± 0.002	0.008 ± 0.003	0.001 ± 8 * 10^{-4}
Flight	Frontal	0.019 ± 9 * 10^{-4}	0.021 ± 0.005	0.008 ± 0.002
	Sagittal	0.131 ± 0.031	0.092 ± 0.018	0.08 ± 0.017
	Transverse	0.010 ± 0.002	0.006 ± 9 * 10^{-4}	0.004 ± 4 * 10^{-4}
Hand Contact	Frontal	0.020 ± 6 * 10^{-4}	0.005 ± 0.002	0.006 ± 0.001
	Sagittal	0.187 ± 0.023	0.022 ± 0.002	0.045 ± 0.011
	Transverse	0.015 ± 0.002	0.005 ± 6 * 10^{-4}	0.004 ± 7 * 10^{-4}
Landing	Frontal	0.008 ± 0.001	0.010 ± 0.002	0.005 ± 0.002
	Sagittal	0.054 ± 0.011	0.030 ± 0.005	0.029 ± 0.023
	Transverse	0.005 ± 7 * 10^{-4}	0.006 ± 5 * 10^{-4}	0.004 ± 0.002

trailing leg to limit the hip abduction angle, thus controlling frontal plane H and reducing point deductions. These results are consistent with kinetic asymmetries observed in the arms, specifically higher forces on the side of the leading leg, during the front handspring on the floor (Exell et al., 2016).

4.2. Relationships between demographics and BHS performance

Despite the multitude of variables that goes into calculating point deductions, the correlation between the BHS frontal plane H_R and point deductions supports the use of angular momentum as an important metric in the BHS performance. The correlation between BHS sagittal plane H_R and the skill level of the gymnast suggests that as the gymnast becomes more skilled, they produce larger motions in the sagittal plane about their CoM (a larger split in the legs during the BHS) and can generate more angular momentum. This correlation could be seen as a measure of the gymnasts' confidence in their abilities on the beam increasing as they are able to better generate angular momentum. These results are consistent with other research that found differences between unskilled and skilled gymnasts with lower GRFs and faster joint velocities in the skilled gymnasts' BHS (Kampschroeder et al., 1997). Furthermore, more skilled gymnasts had improved postural control (i.e., smaller center of pressure displacements) and more effective muscle activity patterns to control center of pressure sway when performing a handstand (Kochanowicz et al., 2018).

5. Limitations

A potential limitation of this study was the use of a balance beam on the floor. A competition balance beam is 1.25 m high and made out of different material than the beam used in this experiment, which might

Table 3
Comparison of the values of peak-to-peak whole body angular momentum (H_R), across the entire back handspring (mean ± standard deviation), normalized by mass * height^2.

	Frontal Plane	Sagittal Plane	Transverse Plane
H_R (1/s)	0.066 ± 0.011	0.453 ± 0.013	0.030 ± 0.006

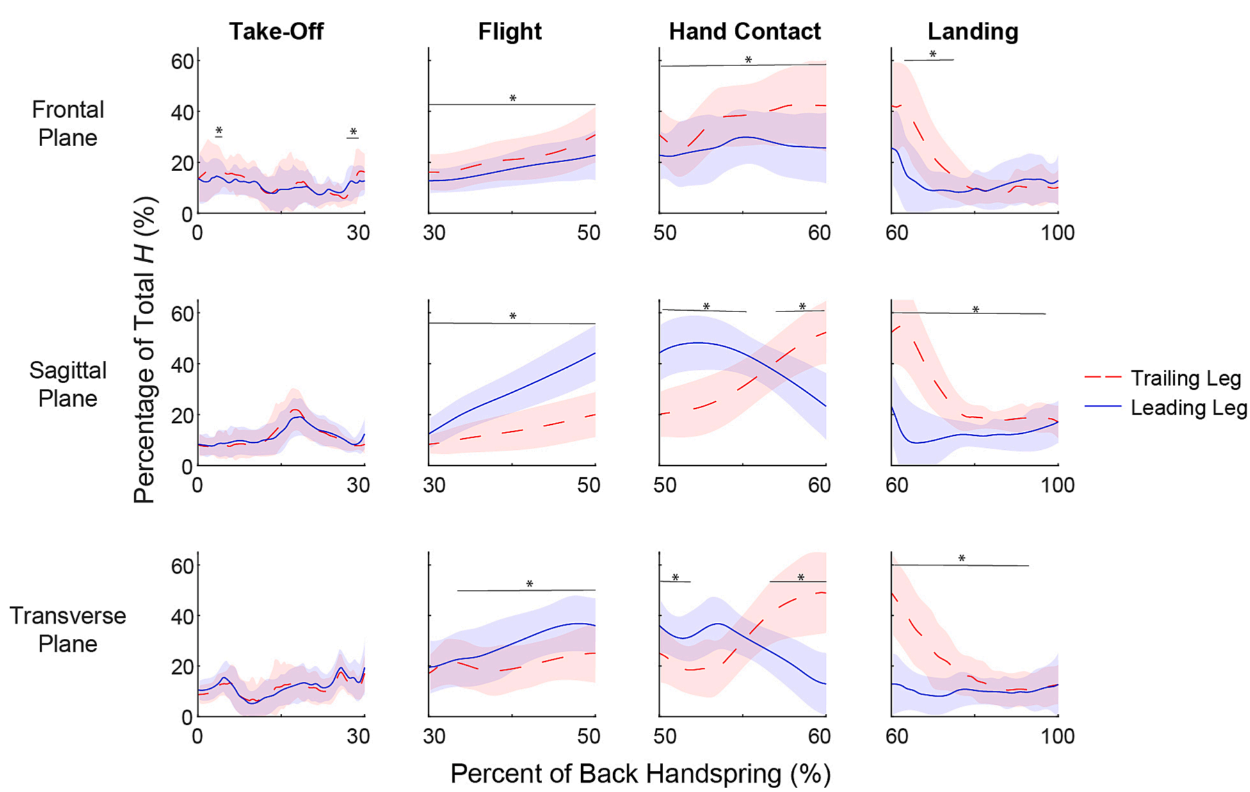

Fig. 3. Leg contributions to whole-body angular momentum (H) (normalized to 100 % of the skill). The percent of the phases were averaged across gymnasts and thus are approximations. The dashed line represents the trailing leg and the solid line represents the leading leg. "*" indicates significant difference between the leading and trailing legs ($p < 0.05$).

alter the elasticity of the beam and the resulting kinematics. However, the softer floor beam was used to ensure the safety of the gymnasts. We also provided a brief subjective survey following each gymnast's participation and found on average the beam did not affect their performance (18 gymnasts said the beam did not affect their performance, 3 said the beam felt slippery and soft and 4 said the beam felt hard). Furthermore, our analysis only encompassed BHSs that did not include a fall or were significantly off balance, which limits our results to successful BHSs. However, the few BHSs that were excluded (n = 9/75) were so off balance that H_R included balance recovery strategies in addition to the BHS. Future work should investigate how the center of mass position relative to the center of the beam differentiates these successful and unsuccessful back handsprings.

6. Conclusions

Given the popularity and risks in gymnastics, more research is needed to understand the neuromuscular control and biomechanics of various skills to guide training routines and help minimize injury risk. This work found that the trunk segment was the largest contributor to angular momentum generation and control during the second half of low-scoring BHSs, emphasizing the important role of the trunk during the BHS. Thus, training routines should focus on the trunk generating the needed angular momentum in the BHS, as well as engaging the trunk muscles during the flight phase to control the trunk motion in the air. Furthermore, the trailing leg was a larger contributor to angular momentum than the leading leg, further highlighting the need to minimize hip abduction in the trailing leg to regulate its angular momentum and improve the BHS performance.

CRediT authorship contribution statement

Gabriella H. Small: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Richard R. Neptune:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Subject demographics for each subject and mean ± standard deviation

Subject number	Age (years)	Height (cm)	Mass (kg)	Skill Level in Gymnastics (1–10)	Years of Training in Gymnastics (years)	Leading Leg (Left/Right)
1	24	162	53.0	7	17	L
2	23	165	53.0	7	5	L
3	20	154	54.6	9	15	L
4	11	144	38.5	7	8	L
5	18	158	54.0	8	15	R
6	17	156	56.5	10	14	R
7	14	156	45.8	10	13	R
8	14	157	55.5	10	10	R
9	14	150	46.5	9	12	R
10	14	156	45.4	9	11	R
11	22	154	50.0	7	15	R
12	11	148	52.0	7	4	L
13	11	146	39.0	8	7	R
14	20	150	74.5	8	14	R
15	13	155	43.8	7	10	R
16	17	151	52.5	10	11	R
17	19	160	63.0	8	17	L
18	19	154	49.5	8	16	L
19	19	165	57.0	8	15	R
20	10	132	29.0	6	5	R
21	14	162	45.4	9	11	L
22	17	163	59.0	10	14	R
23	14	159	50.0	8	12	R
24	15	155	43.5	9	13	R
25	13	153	44.0	8	11	R
Average	**16.1 ± 3.9**	**154.7 ± 7.3**	**50.2 ± 8.9**	**8.3 ± 1.2**	**11.8 ± 3.7**	**8 Left/17 Right**

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