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The relationship between back handspring step out performance and take-off technique in female gymnasts

Gabriella H. Small and Richard R. Neptune

Walker Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX, USA

ABSTRACT

Although the back handspring step out (BHS) is a foundational skill in balance beam routines, it can be performed using different take-off techniques. Back injuries are highly prevalent in the BHS due to the combination of high spine extension and joint loading. However, it is unclear which technique minimises injury risk or leads to better BHS performance. The purpose of the study was to identify techniques used for the BHS take-off and analyse the resulting BHS performance. Gymnasts were found to use either: Simultaneous Flexion—trunk and knees flex at the same time; Sequential Flexion—trunk reaches its maximum flexion followed by knee flexion; or Double-Bounce—knees and trunk both flex and then the knees extend and flex again. To assess performance, point deductions were calculated, and dynamic balance, ground reaction forces (GRFs) and relevant joint angles were analysed. The techniques had no differences in point deductions or dynamic balance, but there were differences in GRFs, spine extension and knee flexion. The Sequential Flexion technique had the lowest spine extension, which potentially reduces back injuries and the lowest knee flexion, which is a BHS requirement. These results support the use of Sequential Flexion technique when performing the BHS.

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Gymnastics; balance control; technique; balance beam

Introduction

Despite the popularity of gymnastics (Sports and Fitness Industry Association, 2019), little research has examined the biomechanics of various gymnastics skills and how the techniques used relate to their performance (Farana et al., 2023). While gymnasts are judged in competition based on kinematic requirements outlined in the Code of Points (Fédération Internationale de Gymnastique, 2022), a gymnast can perform skills using different techniques while satisfying those requirements. Given the high biomechanical demands of various skills in gymnastics, a better understanding of the techniques used is crucial for coaching and targeted training routines (Farana et al., 2023).

The back handspring step out (BHS) in women's artistic gymnastics is a foundational skill that occurs in balance beam routines starting as young as 10 years old through collegiate and Olympic competitions (Fédération Internationale de Gymnastique, 2022). Previous studies have investigated the differences in the kinematics of the BHS for gymnasts with and without back pain (Pimentel et al., 2020), because back injuries are highly prevalent in gymnastics and

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CONTACT Richard R. Neptune rneptune@mail.utexas.edu

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from the BHS specifically (Goldstein et al., 1991; Hall, 1986; Jackson et al., 1976) due to the combination of high spine extension and joint loading (Kruse & Lemmen, 2009). Therefore, determining a technique that reduces the amount of spine extension could help mitigate back injuries, as limiting lumbar extension is a common treatment for certain back injuries (Standaert, 2002). Some studies have investigated a two-footed BHS on the floor, a variation of the BHS, by analysing impact loads on the shoulder (Davidson et al., 2005), moments at the elbow (Koh et al., 1992) and hand positioning (Burton et al., 2017), and have suggested that certain techniques could lead to a reduction in injuries (Burton et al., 2017; Koh et al., 1992). Others have observed unique biomechanical demands in the BHS uncommon in daily activities, such as high elbow valgus moments (Koh et al., 1992). Furthermore, previous studies in tumbling suggested that the elements of the take-off technique can affect the resulting performance (Brüggemann, 1988; King & Yeadon, 2003). However, few studies have investigated the specific kinematics and balance control of a BHS when constrained on the balance beam (e.g., Ede et al., 2021; Pimentel et al., 2020). The small margin of stability (Hof et al., 2005) on a balance beam requires more tightly controlled frontal plane balance and different kinematics than a two-footed BHS on the floor (Ede et al., 2021; McLaughlin et al., 1995), and different techniques could affect the resulting performance.

Multiple variations in technique can lead to a successful BHS on a balance beam, but they remain largely understudied in terms of performance or injury risk (e.g., Burton et al., 2017; Ede et al., 2021). The Code of Points defines a successful BHS as one that minimises point deductions related to maintaining balance, body alignment, precision and height of the skill as well as minimising knee or elbow joint flexion after take-off, among other faults (Fédération Internationale de Gymnastique, 2022). While some studies have assessed the technical merits and injury risks of different hand position techniques (Burton et al., 2017; Richter & Boucher, 2017) and elbow flexion at hand contact (Koh et al., 1992) in a BHS, fewer studies have investigated the take-off techniques used in a BHS. The specific demands of the countermovement during take-off require the gymnast to produce vertical, backward and angular momentum, with multiple techniques capable of successfully generating all three (Fédération Internationale de Gymnastique, 2022). However, these take-off techniques have not been previously identified nor characterised in terms of performance or back injury risk. Therefore, the purpose of this study was to identify the techniques used for the BHS take-off and analyse the resulting BHS performance. To assess performance, point deductions were calculated, and dynamic balance, ground reaction forces (GRFs) and relevant joint angles were analysed. We hypothesise that one technique will maximise the BHS performance and minimise back injury risk relative to the others.

Materials and methods

Data collection

Twenty-five female gymnasts between 10 and 25 years old were recruited from the local community (Table 1) to ensure the data captured a wide variety of techniques and had statistical power of at least 0.8. All subjects provided informed consent to participate in this protocol approved by the Institutional Review Board. All participants were free from any musculoskeletal and neuromuscular injuries that would affect their performance of a BHS on a balance beam. 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 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.

Table 1. Subject demographics (mean ± standard deviation). The skill level was determined by the level (1–10) the gymnast competed in their previous gymnastics season.

	Total Average	Simultaneous Flexion Technique	Sequential Flexion Technique	Double-Bounce Technique
Age (years)	16.1 ± 3.9	17.7 ± 4.8	15.0 ± 2.9	15.1 ± 2.7
Height (cm)	154.7 ± 7.3	155.8 ± 7.7	151.0 ± 10.7	155.3 ± 4.5
Mass (kg)	50.2 ± 8.9	50.1 ± 7.2	46.9 ± 9.3	52.7 ± 9.3
Skill Level in Gymnastics (1–10)	8.3 ± 1.2	8.1 ± 1.2	8.6 ± 1.7	8.1 ± 1.1
Leading Leg (Left/Right)	8 Left/17 Right	4 Left/6 Right	1 Left/4 Right	3 Left/7 Right

Participants were given as much time as needed to warm up in order to perform the BHS. They then completed three BHSs on the balance beam with the instruction to perform as if you were on a high-beam in a competition. Each trial was repeated if the participant fell off the beam ($n = 9$ of the 75 trials). Following the protocol, a brief survey was given to assess their opinions of the balance beam and their BHS performance.

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. A 15-segment inverse dynamics model was created for each subject using Visual3D (C-Motion, Germantown, MD, USA), including the feet, shanks, thighs, pelvis, thorax, abdomen, upper- and fore-arms and hands. GRFs were normalised by body mass, and the maximum peak and impulse of the mediolateral (ML), anterior-posterior (AP) and vertical GRFs were calculated during the take-off phase. The GRFs were time normalised to 100% of the take-off, where 0% and 100% represented the start and end of the take-off phase, respectively. The take-off phase was defined as the start of the skill (i.e., when centre of mass (CoM) velocity begins to increase) until the toes leave the ground (i.e., when the vertical GRF = 0). Hand contact was defined as when the hands touched the beam (i.e., the vertical GRF > 0). The BHS trials ended when the magnitude of the CoM velocity came to zero at the end of the skill. After all the kinematics of all the joints were analysed from preliminary data, the knee and trunk flexion had the highest variability in the timing of the peak joint flexion (standard deviation = 10.1% of the BHS) across subjects, and therefore were the focus for determining the different techniques. Three different preferred BHS take-off techniques were identified across the gymnasts (Figure 1). Technique 1 (Simultaneous Flexion) was characterised by the trunk and knees flexing at the same time during take-off. Technique 2 (Sequential Flexion) was characterised by the trunk reaching its maximum flexion followed by knee flexion at take-off. Technique 3 (Double-Bounce) was characterised by the gymnast performing a ‘double-bounce’ (i.e., knees and trunk flexing at the same time and then the knees extending and flexing again to produce a second countermovement). Specifically, the gymnasts were categorised into Technique 2 (Sequential Flexion) if the knee flexion angle did not change when the trunk flexed at the beginning of the take-off, they were categorised into Technique 3 (Double-Bounce) if the knees extended more than 10% of the total knee flexion during the take-off phase (which delineated the initiation of the second bounce), and they were categorised as Technique 1 otherwise.

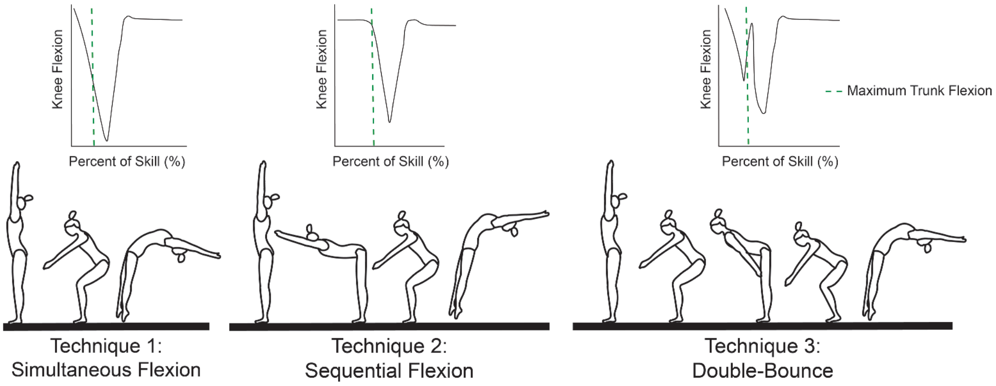

Figure 1. Schematic of the three different techniques for the back handspring step out (BHS). The top plots represent knee flexion across the skill, and the dotted line shows where the trunk reaches its maximum flexion.

Dynamic balance was quantified using whole-body angular momentum (H), which was calculated by summing the angular momentum of each body segment about the whole-body CoM. H was normalised by subject mass and height. The range of H (H_R) was calculated in both the frontal and sagittal plane, which was defined as the difference between the peaks of H over each BHS, where lower H_R indicates more tightly controlled balance (Herr & Popovic, 2008; Neptune & Vistamehr, 2019). The joint angles analysed included spine extension at hand contact, peak knee flexion after take-off, peak hip flexion after take-off, wrist flexion at hand contact, elbow flexion at hand contact and shoulder flexion at hand contact. To determine spine extension angle, the angle between the thorax and abdomen segments was calculated. Trunk flexion was defined as the thorax and abdomen segments going into flexion (i.e., the trunk moving towards the legs).

To determine the height of the skill, both the maximum peak vertical CoM and the maximum pelvis height were examined. The maximum pelvis height was chosen in addition because the CoM can be highly variable in a BHS and dependent on other kinematic variables, such as arm and leg positions or the spine extension angle.

Any trial where the gymnast wobbled such that their peak joint angles were more than three standard deviations from the group mean value were excluded. To quantify the BHS point deductions, each BHS was evaluated by a trained expert using the Code of Points (Fédération Internationale de Gymnastique, 2022), and total point deductions were calculated for each trial. The BHS kinematics were time normalised to 100% of the skill, where 0% and 100% represented the start and end of the skill, respectively.

Statistics

One-way analyses of variance (ANOVA) were used to assess differences in the outcome measures for the BHS (GRF peak and impulse, maximum vertical peak CoM and pelvis height, frontal and sagittal plane H_R, spine extension at hand contact, peak knee flexion after take-off, peak hip flexion after take-off, wrist flexion at hand contact, elbow flexion at hand contact, shoulder flexion at hand contact and point deductions) across the techniques. If the ANOVA revealed significant effects, Tukey HSD post-hoc tests were performed to identify pairwise differences between techniques and to correct for errors due to multiple comparisons. Differences in timing in continuous variables (ML, AP and vertical CoM and CoM velocity) between techniques were assessed using statistical parametric mapping parallel of a t-test (Pataky, 2012), which identified normalised time points where the techniques differed significantly. Significance levels were set at $p < 0.05$.

Results

Take-off techniques

Subject demographics, gymnastics skill level and their preferred BHS technique can be found in Table 1. Ten participants preferred the Simultaneous Flexion Technique, five preferred the Sequential Flexion Technique and ten preferred the Double-Bounce Technique. Other spatiotemporal results can be found in Table 2.

Table 2. Spatiotemporal results of the back handspring across the three techniques.

	Simultaneous Flexion Technique	Sequential Flexion Technique	Double-Bounce Technique
Skill Duration (s)	2.60 ± 0.31	3.05 ± 0.47	2.90 ± 0.47
Distance Traveled (m)	1.5 ± 0.19	1.4 ± 0.14	1.5 ± 0.11

Ground reaction forces

The Simultaneous Flexion technique had lower peak AP and vertical GRFs ($p < 0.04$) and impulses ($p < 0.007$) (Figure 2 and Appendices A and B) during the take-off compared to the other techniques. There were no differences in the peak ML GRF or impulse ($p > 0.05$).

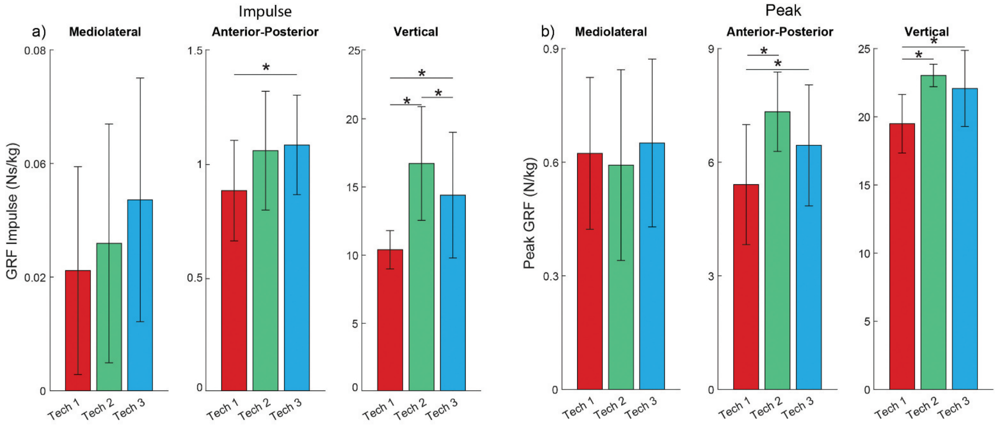

Figure 2. Ground reaction force (GRF) impulse (a) and maximum peak (b) during take-off across the three different techniques (tech 1 = Simultaneous Flexion, tech 2 = Sequential Flexion, tech 3 = Double-Bounce) in the mediolateral, anterior-posterior and vertical directions. GRFs were normalised by body mass. A "*" indicates a significant difference of $p < 0.05$.

Balance control

There were no differences in frontal ($p = 0.588$) (Figure 3(a) and Appendix B) or sagittal ($p = 0.666$) (Figure 3(b) and Appendix B) plane H_R across the different techniques.

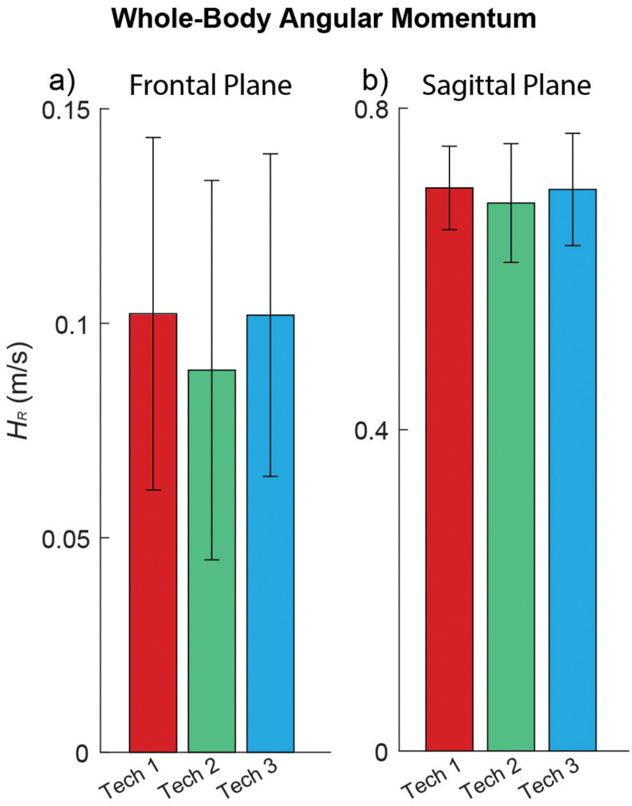

Figure 3. Peak-to-peak frontal (a) and sagittal (b) plane whole-body angular momentum (H_R, normalised by height and mass) across the three different techniques (tech 1 = SimultaneousFlexion, tech 2 = Sequential Flexion, tech 3 = Double-Bounce).

Kinematic differences

There were no differences in peak CoM position across the techniques ($p = 0.692$), but there were differences in the timing of the peak AP and peak vertical CoM ($p < 0.01$) and CoM velocity ($p < 0.03$) (Figure 4 and Appendix B) and between the Simultaneous and Sequential Flexion techniques' maximum pelvis height ($p = 0.026$) (Figure 5 and Appendix B).

The Simultaneous Flexion had a higher spine extension angle at hand contact ($p < 0.004$) (Figure 6 and Appendix B) as well as higher peak knee flexion after the take-off ($p < 0.012$) than the Sequential Flexion or the Double-Bounce techniques (Figure 7 and Appendix B). There were no differences across techniques in the point deductions ($p = 0.124$) (Figure 8 and Appendix B). Finally, there were no differences across techniques in peak hip flexion after take-off or in shoulder, wrist or elbow flexion at hand contact ($p > 0.05$).

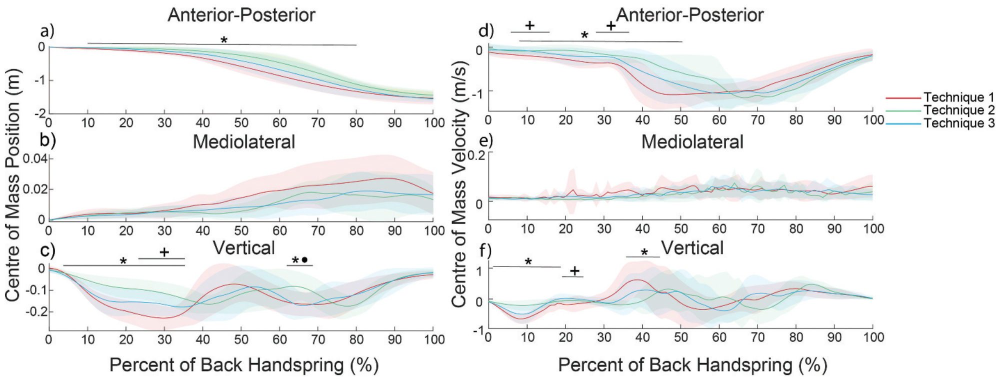

Figure 4. Centre of mass position (a–c) and velocity (d–f) of the back handspring in the anterior-posterior (a, d), mediolateral (b, e) and vertical (c, f) direction across the skill, normalised to 100% of the skill. The color represents the technique with red = technique 1, green = technique 2 and blue = technique 3. A "*" indicates a significant difference between techniques 1 and 2, a "+" indicates a significant differences between techniques 1 and 3 and a "·" indicates a significant difference between techniques 2 and 3 of $p < 0.05$ determined by statistical parametric mapping (technique 1 = Simultaneous Flexion, technique 2 = Sequential Flexion, technique 3 = Double-Bounce).

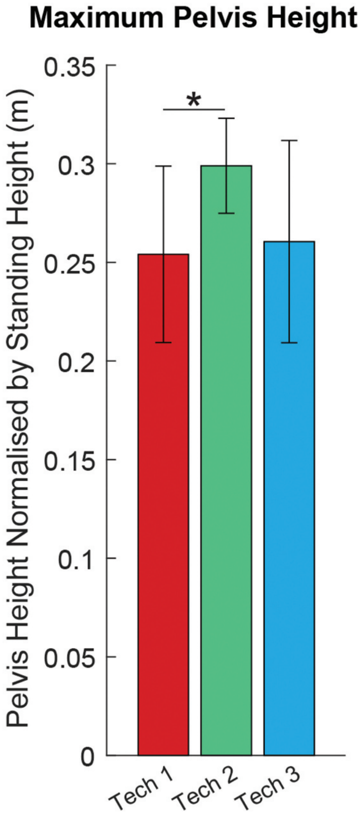

Figure 5. The differences in the maximum vertical pelvis height across the three techniques (tech 1 = Simultaneous Flexion, tech 2 = Sequential Flexion, tech 3 = Double-Bounce). A "*" indicates a significant difference of $p < 0.05$.

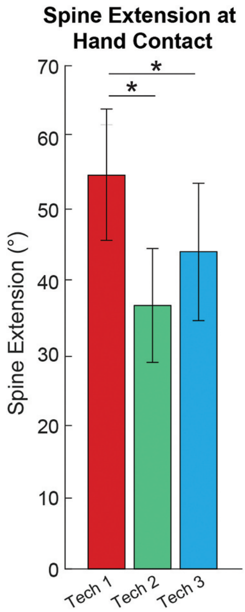

Figure 6. Differences in spine extension angle at hand contact across the three techniques (tech 1 = Simultaneous Flexion, tech 2 = Sequential Flexion, tech 3 = Double-Bounce). A "*" indicates a significant difference of $p < 0.05$.

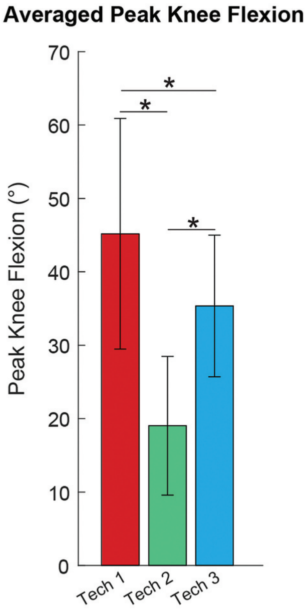

Figure 7. Averaged left and right peak knee flexion angle after the take-off across the three techniques (tech 1 = Simultaneous Flexion, tech 2 = Sequential Flexion, tech 3 = Double-Bounce). A knee flexion angle of 0 degrees is considered the correct technique and results in no point deductions (Fédération Internationale de Gymnastique, 2022). A "*" indicates a significant difference of $p < 0.05$.

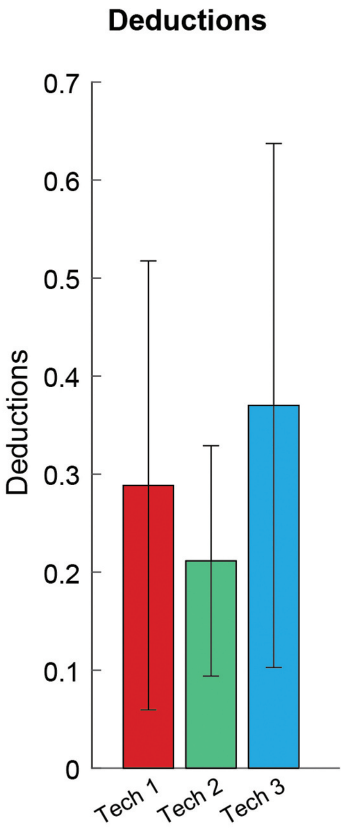

Figure 8. Point deductions calculated for the BHS across the three techniques (tech 1 = Simultaneous Flexion, tech 2 = Sequential Flexion, tech 3 = Double-Bounce). Deductions were taken as described in the Code of Points (Fédération Internationale de Gymnastique, 2022), where 0 represents a perfect skill and 1 point in deductions is taken for a fall off of the balance beam.

Discussion

This study identified three preferred take-off techniques for a BHS on the balance beam (Simultaneous Flexion, Sequential Flexion and Double-Bounce) and then determined if the take-off technique used influenced the BHS performance. We hypothesised that one technique would maximise the performance of the BHS and minimise back injury risk relative to the others, which was partially supported by differences in GRFs and some kinematic data but not in balance control or point deductions. The results of this study support using the Sequential Flexion technique over the Simultaneous Flexion or the Double-Bounce technique.

Previous work in other gymnastics skills found that gymnasts can use a variety of techniques, such as differences in hand positioning or joint angles (e.g., Burton et al., 2017; King & Yeadon, 2003) and that slightly changing the technique can be an important factor in injury reduction (Koh et al., 1992). While the different BHS techniques did not result in differences in point deductions (Figure 8), there were important biomechanical differences between techniques. The Simultaneous Flexion technique had lower peak and impulse AP and vertical GRFs than the Sequential Flexion or Double-Bounce techniques, and the Double-Bounce technique trended towards higher AP and vertical GRFs than the Simultaneous Flexion but lower than the Sequential Flexion technique (Figure 2). These differences in GRF peaks and impulses suggest that the Simultaneous Flexion technique requires less muscle demand and the gymnasts likely experience lower joint loading during the take-off than the other two techniques (Kopper et al., 2013), which should be confirmed in future modelling and simulation work.

These changes in GRFs corresponded with specific kinematic differences throughout the BHS. The techniques did not have statistical differences in peak vertical CoM height (Figure 4) due to the high variability in the CoM peak across subjects during the BHS from differences from the rotational motion (i.e., differences in arm and leg position and spine extension angle that affected the CoM location). This lack of a statistical difference in CoM height is consistent with others who found no differences in CoM height between a BHS and two-footed BHS (Ede et al., 2021), and the variability is comparable with other studies on the BHS (e.g., Pimentel et al., 2020). However, these results found that the Sequential Flexion technique had the highest pelvis height (Figure 5), the body segment that reached the highest point during the flight phase of the BHS, consistent with its higher vertical GRF. The techniques also had differences in timing and velocity of the CoM, with the Simultaneous Flexion technique having an earlier peak and faster motion in the AP direction (Figure 4). Because the Simultaneous Flexion technique had a smaller impulse (Figure 2), gymnasts using this technique spent less time on the beam generating force, and thus a faster change in CoM position occurred earlier in the skill (Barker et al., 2018).

The Simultaneous Flexion technique also had the highest spine extension angle at hand contact (Figure 6) out of the three techniques. This spine extension angle coupled with the lower GRFs suggests that the Simultaneous Flexion technique relies more on the spine extension to produce the flipping motion. In contrast, the Sequential Flexion technique had higher GRFs and lower spine extension, suggesting it uses a propulsive technique that relies more on push-off from the ground to produce the flipping motion. The Double-Bounce technique was in between the Simultaneous Flexion and Sequential Flexion techniques. Overall, these results highlight that differing take-off techniques lead to differences in spine extension at hand contact. High repetitive spine extension can lead to back pain and injuries (Kruse & Lemmen, 2009), and the BHS is a common cause of spine injuries in gymnasts (Hart et al., 2018). Thus, using the Sequential Flexion technique may be beneficial for reducing lower back pain and injury risk compared to the other two techniques.

Finally, there were no differences in the point deductions across techniques (Figure 8), which was likely due to the multitude of variables that goes into calculating point deductions (Fédération Internationale de Gymnastique, 2022). Given the wide range of skill level in the present study and the inclusion of high level gymnasts executing all three techniques (Table 1), it was unsurprising that no technique was significantly lower scoring than the others. However, there were significant differences in knee flexion during the skill (Figure 7), which contributes to point deductions (no knee flexion = 0 point deductions but large knee flexion = 0.5 point deductions). Lower knee flexion after take-off during the skill is preferable (Fédération Internationale de Gymnastique, 2022), and the Sequential Flexion technique had significantly lower knee flexion angles (Figure 7), further supporting the use of the Sequential

Flexion technique. These results are consistent with the idea that the Sequential Flexion technique relies more on push-off from the ground and in turn leads to a full extension of the knees and higher pelvis height (Figure 5). However, there were no differences in the arm kinematics (e.g., shoulder, wrist or elbow angles) or balance control (Figure 3) between techniques, which also contributes to point deductions (Fédération Internationale de Gymnastique, 2022). Despite these benefits of the Sequential Flexion technique, the Simultaneous Flexion technique may be popular due to its similarities to how a two-footed BHS on the floor is performed (Fédération Internationale de Gymnastique, 2022). Given the similarities in point deductions between the techniques, gymnasts may naturally transfer this technique to the BHS on the balance beam without consideration of future injury risk.

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 alter the elasticity of the beam and the resulting kinematics. However, the softer floor beam was used to ensure the safety of the gymnasts. In addition, the brief survey following each subject's participation revealed 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, due to safety reasons, each gymnast only performed their preferred technique, and thus within-subject comparisons were not possible. However, each technique contained a similar spread of skill level and subject demographics, and each gymnast was able to complete a BHS on the high beam confidently to minimise any differences due to skill level. Finally, the point deductions were determined by a trained expert, and thus included some subjectivity. However, all gymnasts underwent the same evaluation, and these subjective measures were confirmed with the kinematics and joint angles of each BHS.

Conclusion

Given the importance of the BHS as a foundational skill on the balance beam, a better understanding of the underlying BHS biomechanics is crucial. While there were no differences in overall point deductions between the three take-off techniques, there are important considerations that gymnasts should consider. Variations in the take-off of the BHS led to differences in the GRFs, spine extension at hand contact and knee flexion during the skill. Future modelling work should also consider differences in muscle demand and joint loading across the three techniques given the differences in GRFs. Reducing spine extension, especially in a skill that is repeated as frequently as the BHS, is an important step in reducing injury risk. Even though the Sequential Flexion technique had higher GRFs, it had the lowest spine extension at hand contact, which can help mitigate back injuries. The Sequential Flexion technique also had the lowest knee flexion, which is beneficial for point deductions. Both of these results support using the Sequential Flexion technique over the other two techniques in a BHS on a balance beam to mitigate back injuries as well as improve performance. These results also emphasise that gymnasts who already use the Simultaneous Flexion or Double-Bounce techniques should focus on achieving full extension of the knees after take-off to improve performance. These results provide further insight into the coordination necessary to perform a BHS and guidelines for training regimens to improve the performance of the BHS while minimising injury risk.

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