REACHING A CHEERLEADING COMPETITION-READY BACK HANDSPRING

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ABSTRACT

The MIT Cheerleading team struggles to achieve competitive success due to a lack of strong tumblers. New tumblers start with back handsprings, a fundamental tumbling skill, from standing on a spring floor, but must perform from a round-off on mat floor at competition. Video was taken at 240 Hz to track markers on the ankle, knee, hip, shoulder, elbow, and waist to characterize how the back handspring changes when performed from standing and running entries and on spring and mat floors. Key parameters of the back handspring were largely indistinguishable across testing conditions. However, standing and running back handsprings showed large differences in momentum change between initial takeoff and final landing. This suggests that after learning the basic motion of the back handspring from standing, new tumblers could more easily achieve the running back handspring first because it is significantly less demanding of the arms.

INTRODUCTION

The Massachusetts Institute of Technology Cheerleading Team is largely composed of new and inexperienced cheerleaders. While they can achieve new stunts and tosses very quickly, it is hard for adults to pick up tumbling skills that are usually learned as children. Tumbling is the subset of gymnastics maneuvers that occur on the floor, and can affect up to 20% of competition scores. In order to be competitive, there is a need to train tumblers, starting with back handsprings.

The back handspring is a fundamental tumbling skill often used after a round-off to ramp up to more advanced skills. A tumbling pass that starts with a round-off is called a running pass, whereas a skill executed on its own is called a standing skill. MIT Cheerleading practice occurs on rubber mats attached over an array of springs (hereafter referred to as "spring floor"). However, during competition, the rubber mats are laid directly on a concrete floor ("mat floor").

Only a few of MIT's cheerleaders have succeeded at learning the back handspring in the limited time before competition. To try to improve this number, a better understanding of the motion can be gained through video analysis. However, after obtaining a back handspring from standing on the spring floor, it must be connected to a round-off and executed on mat floor. Thus, it is also important to understand how the tumbling surface and the entry method affect the needs and outcome of the back handspring.

While many studies exist on elite gymnasts, this study focuses on a single cheerleader as she performs several standing and running back handsprings, first on mat floor and then spring floor. The trajectories of the ankle, knee, hip, shoulder, elbow, and wrist were tracked to determine key parameters that characterize the flight of a back handspring. Finally, the velocity of her center of mass was calculated to understand the varying momentum changes. Ideally, the results can be used to provide insight on whether or not there is a method in which the skills would be best learned.

BACKGROUND AND THEORY

THE MOTION OF A BACK HANDSPRING

First, it is important to understand the basic requirements of a back handspring. To start the standing back handspring shown below in Figure 1, the tumbler leans back while bending at the knees before jumping backwards. The motion is like sitting back into a chair, knees bent close to 90 degrees; bending much more or less limits the tumbler's jumping potential. The hips should be behind the ankles to initiate the backwards motion. The jump should have approximately equal backwards and upwards motion in order to gain maximum travel across the floor while also having time to swing the arms around. The arm swing also provides extra momentum to the jump. Once in the handstand, the rebound force should be produced by a shrug in the shoulder, without bending at the

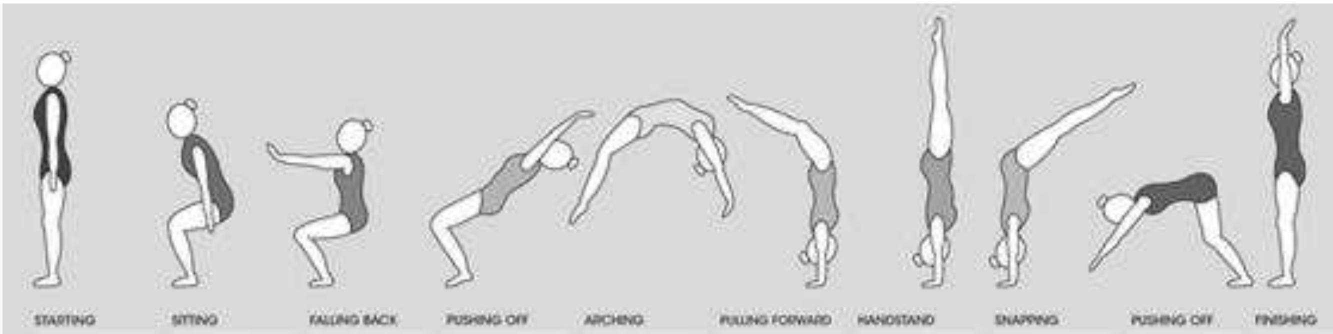

Figure 1: A complete standing back handspring. The tumbler first sits back before jumping equally backwards and upwards and swinging her arms over her head into a handstand. While in the handstand, the tumbler rebounds with a shrug of her shoulders, and then snaps her legs back down to finish. Adapted from [1].

elbow. Finally, the tumbler needs to use her abdomen to control the snapping of her legs back down to the ground and into a standing position.

The most difficult part of the back handspring is the handstand, when the tumbler's arms must support a large collision force and then provide enough energy to push off the ground again. If the elbows bend or the wrists are placed too far apart, the force is even more difficult to hold. Assuming tumblers subconsciously optimize their back handsprings over time to minimize the force on their arms, the parameters of their motion can provide a comparison model for learning tumblers. Furthermore, tracking changes in the parameters across different floor surfaces and entry methods may show how tumblers compensate for increased execution difficulty in certain conditions.

CHOICE OF KEY PARAMETERS

In the most relevant previous study, a group of researchers led by Lovecchio measured thirteen key technique variables of a back handspring that were defined by a consulted national gymnastics team trainer [2]. These thirteen key variables split characterization into four phases: preparation, first flight, handstand, and second flight. In Figure 1, preparation occurs from "Starting" to "Pushing Off," first flight occurs from "Pushing Off" to "Pulling Forward," handstand occurs from "Pulling Forward" to "Snapping," and second flight occurs from "Snapping" to "Finishing." (Note that the measured parameters are briefly described below but are illustrated in Section 3.4 if an additional image is necessary for understanding.)

The national trainer determined that in the preparation phase, key parameters included the knee bending angle, the back-projection of the hip, and the distances between the left and right ankles and knees. The knee bending angle is the angle between the calf and thigh before the tumbler starts pushing off, where the angle is at a minimum. The back projection is the horizontal distance between the ankle and hip at this time. The knee bending angle and the distances between the left and right ankles and knees play a big role in the force that can be exerted during the jump, whereas the back projection foreshadows the direction of the jump.

First flight consists of the transition from feet to hands. In particular, the escape angle and trunk-thigh angle were measured at takeoff along with the length of the flight. The flight length is the distance travelled along the mat during the first flight and is an important aesthetic feature. The flight length is dependent on the escape angle, which is the angle between the legs and the ground at takeoff, and the trunk-thigh angle, which is the angle formed by the knee, hip, and shoulder. To have good technical form, the thigh-trunk angle should be 180 degrees [2], in which case a 45 degree escape angle would produce the maximum flight length when treating the body as a projectile [3]. But when the trunk-thigh angle is much less than 180, the first flight is significantly shortened and the trajectory looks like a circle rather than the ideal arch.

Next, in the handstand, Lovecchio measured the difference between the initial length of the arm and its minimum length in the handstand to characterize the amount of shoulder shrugging. When their arms are straight and vertical, gymnasts can support more of the force using their bone structure, which requires less use of their arm muscles.

Finally, a key feature of the second flight is the second flight length, which is the distance between where the hands touch off and the feet land once again.

Based on Lovecchio's results, the back handspring could be approximated as a two-dimensional motion. The difference between the hip back-projection on both sides was less than 5% for every tested gymnast. Furthermore, most of the gymnasts had very close parallelism between the line of the feet at takeoff and the line of the hands in the handstand [2]. Many other studies assumed symmetry between the left and right sides, so this experiment will also be constricted to a planar analysis.

MOMENTUM CHANGES IN THE BACK HANDSPRING

Lastly, the execution of a tumbling skill can be explained analytically through the impulse-momentum relationship

$$Ft = mv_f - mv_i \tag{1}$$

where F is the applied force, t is the duration of application, m is the mass of the body, and v_i and v_f are the initial and final velocity of the body. It is important to both apply a great force and to apply it over an amount of time. For example, a possible error in a back handspring is to pull the feet off the ground too early out of the fear of failing to rotate enough. However, this reduces the time of the force application and thus makes it harder to get around [5]. Other examples of the impact of this relationship include the use of various arm swinging motions to produce different takeoff impulses and the need to bend the knee to give sufficient time to pick up momentum.

This equation can also be approached from the other direction. Since the round-off in a running back handspring provides a higher initial velocity to the tumbler, a smaller force would be required to reach the same final velocity. For this reason, running skills are often said to be easier than standing skills. Thus it becomes interesting to see how the initial forward momentum affects a successful back handspring.

SETUP OF PREVIOUS EXPERIMENTS

Many studies exist where important points on the body were tracked in 3D coordinates to characterize the trajectory of the gymnast through a tumbling skill. Their methods used multiple cameras tracking reflective spherical markers at 100 Hz [2,6] or 200 Hz [4,7] to create a 3D motion history. Two experiments additionally analyzed ground reaction forces using plates where the gymnast would land [4,7].

Though takeoff and landing force data would be valuable, it was deemed unsafe for the participating tumbler to aim her landing onto a measurement instrument. There is no access to the underside of the spring floor to place a sensor, and it is also not ideal to change the conditions of the floor while trying to determine its effects. Instead, momentum changes will be studied by analyzing the velocity of points that are tracked in the video.

VIDEO ANALYSIS OF THE BACK HANDSPRING

A time history of the various lengths and angles that characterize body position can be created by recording how parts of the body move between time steps. Video was taken at 240 Hz and was used to track tape markers on the tumbler. Only one cheerleader was analyzed to gain a preliminary understanding without complicating the system with more variables, but she performed six back handsprings in each condition so that statistical analysis could be done.

CAMERA SETUP

A preliminary test showed that 30 Hz video only contained 30-35 frames of video and would not produce smooth trajectory curves. For actual data, a Samsung TL350 with the ability to capture video at 30 Hz, 240 Hz, 480 Hz, and 1000 Hz was used. Since no previous studies needed more than 200 Hz data, the 240 Hz setting was used to produce more than 200 useful frames of data.

This high speed capture setting created several challenges to overcome. The resolution was extremely low and the tape markers were occasionally hard to distinguish even when the camera was turned up to its maximum exposure. There was also noticeable barrel distortion on the top and bottom edges of the screen so the camera was placed on a horizontal surface centered on the back handspring and sufficiently far away so that the back handspring did not fill too much vertical screen space. Ultimately, some video quality had to be given up in order to obtain significantly more data points.

Six trials were taken in each of the conditions. First, the tumbler did six standing back handsprings on the mat floor in the basketball courts, followed by six running back handsprings. Then the testing was moved to the spring floor in the gymnastics room, where again six standing back handsprings were followed by six running back handsprings.

CHOOSING MARKER POINTS

The six markers were approximately 1”-1.5” long by 2” wide rectangular strips of white tape placed over the ankle, knee, hip, shoulder, elbow, and wrist. These points were chosen as the endpoints of each large body segment. The tape was placed over the center of rotation of each joint. Coincident with the center of rotation is a line where the tape’s resistance to motion is least noticeable when bending and unbending the joint. When the joint is fully straightened, this line is also perpendicular to the straightened appendage. This was the chosen location and orientation for the marker so that it would make the smallest impact on the tumbler’s motions and be a repeatable placement location. Shown below is a schematic of the points.

Figure 2: Tape was placed on center of rotation the ankle, knee, hip, shoulder, elbow, and wrist. These points were used to track the motion of all of the major body segments during a back handspring.

TRAJECTORY GENERATION

The videos from the Samsung TL350 were first processed in Windows Movie Maker with the built-in anti-shake/wobbling function. Unfortunately, the resolution of the camera was too low and the markers were not distinctly colored enough to rely on automatic processing because the speed of the motion could blur the marker enough to begin blending in with the tumbler's skin. Instead, manual analysis was done in Logger Pro 3.10.1 where only every other frame was marked to save time. This resulted in a sampling frequency of 120 Hz, which is still within the range of the frequencies at which previous experiments were conducted.

In each frame, the cursor was aimed at the center of the visible marker blobs. After marking each point, the cursor was moved away from the area to avoid biasing the placement of the next point. For any points that were hidden by another moving body part, the arrangement of nearby features was used to estimate the location of the point. The shoulder point in particular was hidden for extended periods of time due to the swinging of the arm, so during manual analysis, the point was selected as the intersection between the line drawn from the top of the arm to approximately the middle of the neck, or the back third of the head. This resulted in the drastically higher uncertainty of the shoulder coordinates so whenever possible, dependency on the shoulder point was avoided.

Below and on the next page are two representations of the data that was obtained. Figure 3 below shows a spatial representation of a skeletal version of the body as it moves through the back handspring. The gray circle represents the head, and the colored x's correspond to the colored body markers in Figure 2. The dashed lines represent the body segments in between each pair of joints. Figure 4 on the next page shows the connected time history of each point's trajectory.

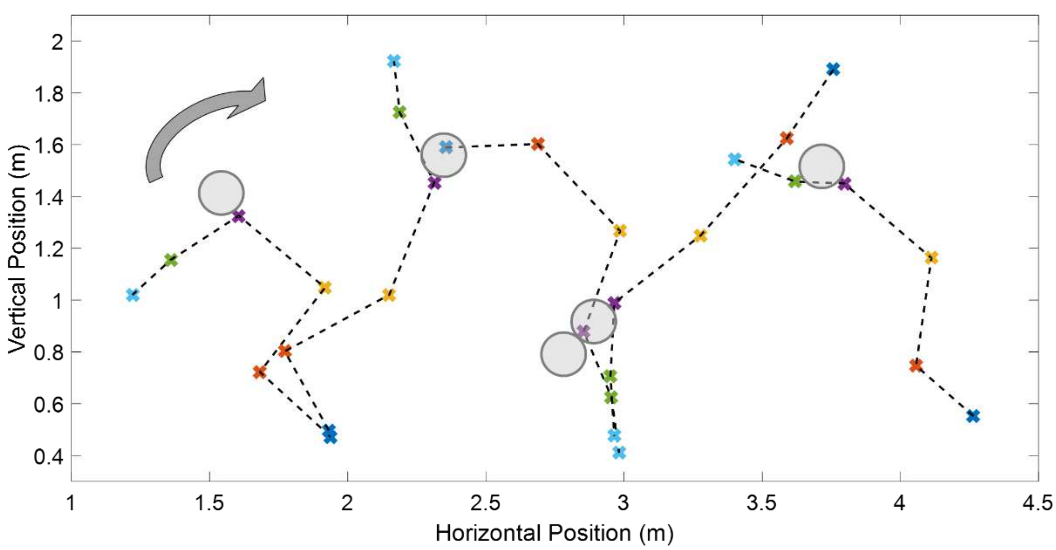

Figure 3: A skeletal depiction of the back handspring on spatial coordinates. The head is represented by the gray circle. Each joint is color-coded according to the silhouette in Figure 2; the color scheme is reproduced in the legend of Figure 4 below. For example, the purple point is the shoulder. Each dashed line is a body segment, so the line between the purple shoulder point and the yellow hip point is the torso.

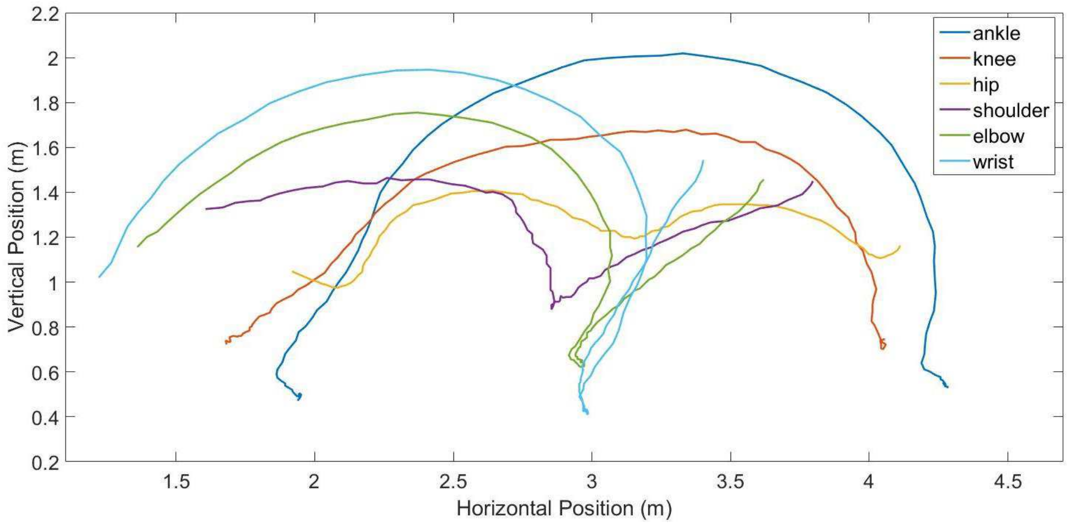

Figure 4: This graph shows the same motion as Figure 3 but contains all of the data from one video as continuous time histories of each joint's motion.

PARAMETER ANALYSIS

Eight parameters were obtained from each generated trajectory. First were the knee bend angle, back projection, escape angle, and trunk-thigh angle. Then the time spent supported by the hands and the concurrent shoulder pushing displacement, or change in shoulder-wrist length, were measured. Finally, the length of the first and second flights were measured. Angles can be calculated using the vectors formed by three markers at a specific timestamp, while lengths can be calculated using the distance between two specific coordinates.

In Figure 5 to the right are depictions of how each parameter was calculated. The condition of contact with the ground was determined by a threshold above which the tumbler was estimated to be airborne. This threshold determined takeoff and landing times for both the wrist and ankle. Most of the measurements were timed by the takeoff or landing threshold except for the knee bend angle and the back projection, which were taken when the knee was bent farthest, indicating the start of the jump. The shoulder pushing displacement was the difference between the maximum and minimum arm length while in the handstand. Meanwhile the handstand time counts the number of frames in which the wrist is below the threshold and converts the duration to a time.

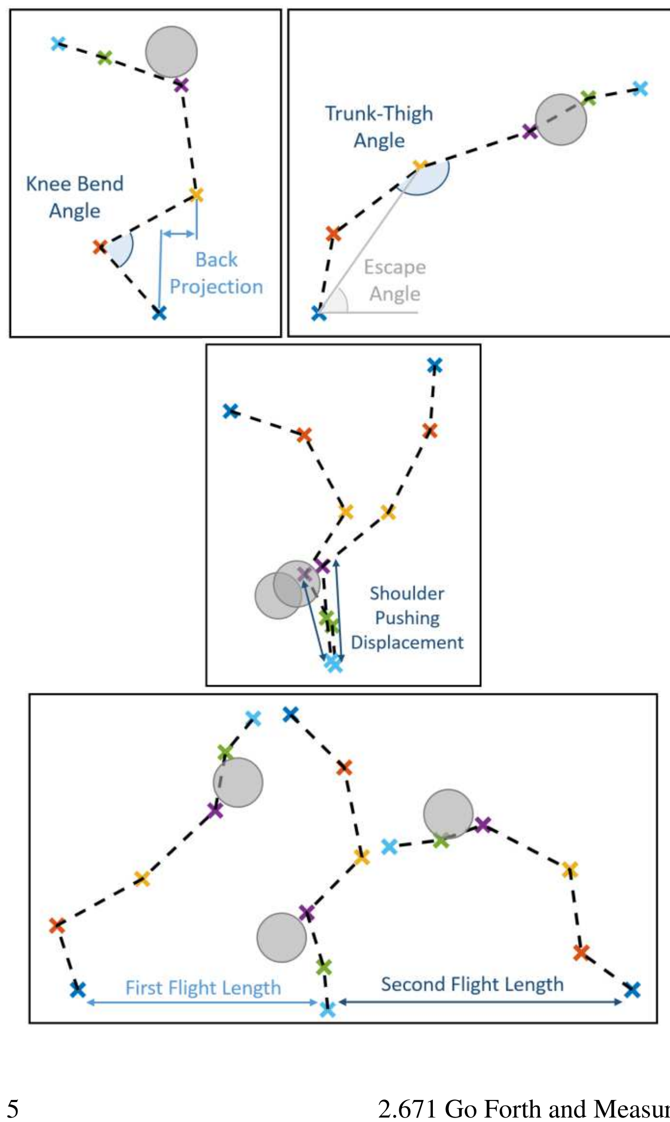

Figure 5 (right)**:** These skeletal drawings show how each parameter is calculated. The gray circle is the head, and the markers use the same color scheme as the silhouette in Figure 2.

MOMENTUM ANALYSIS

Finally, center of mass had to be determined for an analysis of momentum changes. Using a weighted average of the multiple marker coordinates based on the average mass distribution of a 25th percentile human being, the center of mass was approximated using 48% shoulder, 30% hip, 6% elbow, and 16% knee [8]. If this approximation was close, whenever the tumbler was not in contact with the ground, her center of mass would have a downward acceleration equivalent to the acceleration due to gravity and no sideways acceleration.

Using this model of center of mass, the velocity data was still very noisy so the position data were processed using a 9 point moving time average. This sufficiently smoothed the curve to produce single points useful for comparison.

RESULTS AND DISCUSSION

KEY PARAMETERS OF THE MOTION

Ultimately, most key parameters showed very little change. For example, the results from the minimum knee bend angle and takeoff escape angle are shown below. The angles for each condition cannot be distinguished to a 95% confidence. Furthermore, recreational cheerleaders such as those on the MIT team may not be able to produce back handsprings that are consistent within less than 3 degrees so the differences caused by changing conditions could be inconsequential.

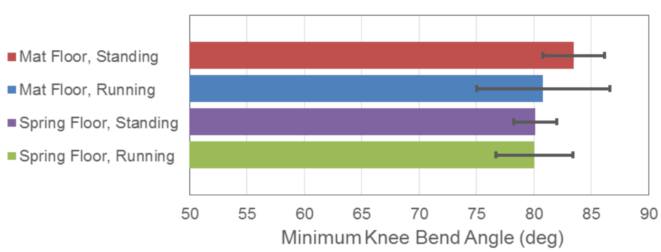

Figure 6: The calculated minimum knee angles based on six trials in each set of conditions. The uncertainty makes it impossible to say with 95% confidence that the values are different.

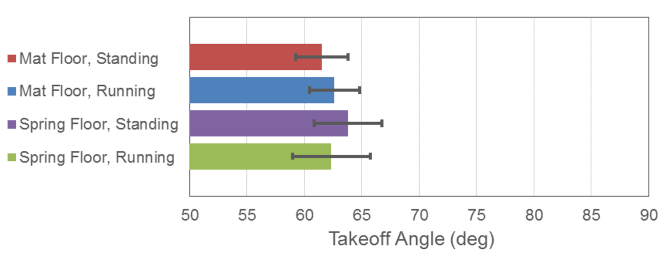

Figure 7: The calculated takeoff escape angle based on the same trials. Again, no trend is apparent.

There are no significant differences between most chosen key parameters. Perhaps there are changes that are not detectable by the method used; for example, Lovecchio also used several parameters that required 3D analysis and thus were ignored, such as the distance between the left and right ankles, knees, and wrists. However, it is likely that there is no way to achieve a back handspring by attempting to adjust body position parameters other than doing a lot of work from the arms in the handstand.

RUNNING VS. STANDING ENTRIES

The only parameter that showed distinctive differences between entry methods was the first flight length. In Figure 8 below, the marked difference in flight lengths between running and standing back handsprings can be seen, though floor elasticity appears to have a weaker effect if any at all.

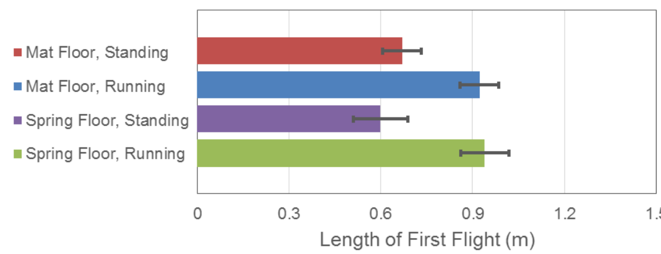

Figure 8: The length of the first flight, or the travel distance between the jump and the handstand landing, based on six trials in each set of conditions. There is a noticeable difference between standing and running back handsprings at the 95% confidence level, though the same cannot be said about the different floor surfaces.

This result is supplemented by a comparison of the center of mass velocities for each entry method. In Figure 9 on the next page, the horizontal velocity profiles (the darker two lines) and vertical velocity profiles (the lighter two lines) for both a standing and a running back handspring are overlaid. The standing back handspring is slightly slower so the time scale was compressed to correspond better to the motions in the running back handspring. Thanks to the running start, running back handsprings have 50-100% more horizontal velocity than standing back handsprings in the first flight. Meanwhile the y velocity profiles are very similar shapes and magnitudes.

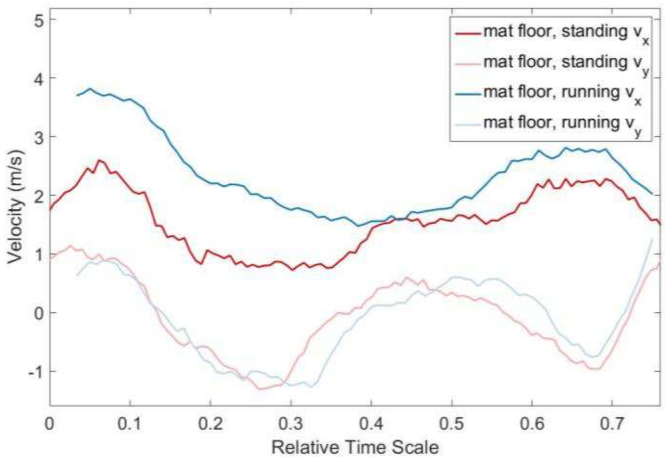

Figure 9: The x velocity profiles of the tumbler's center of mass are drawn by the darker lines while the y velocity profiles are drawn by the lighter lines. The y velocity profiles are similar in shape and magnitude, while the x velocity of the running back handspring (blue) is often 50-100% higher than that of the standing back handspring (red).

The lack of additional horizontal velocity at the beginning of a standing back handspring means that the tumbler had to compensate with a larger push in the handstand phase in order to complete the motion. The bar graph below shows the change in absolute velocity of the tumbler between the initial jump takeoff and the final landing.

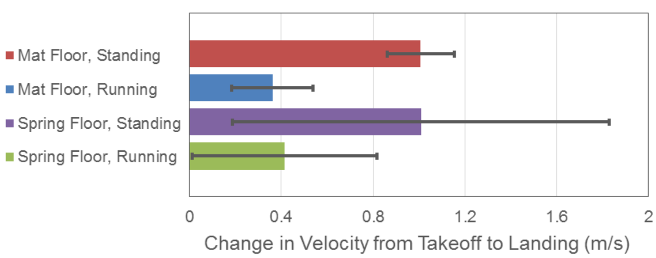

Figure 10: The change in absolute velocity from the tumbler's initial jump takeoff to her final landing on her feet. A running back handspring requires about half the impulse of a standing back handspring when the tumbler is in her handstand. However, this can only be said with confidence based on the results from the mat floor.

Figure 10 suggests that during a standing back handspring the tumbler may have to execute a momentum change that is twice the magnitude as during a running back handspring. However, since this momentum change occurs between takeoff and landing, it must come from the second push-off in the handstand. This means a standing back handspring can be much more demanding on the arms than a running back handspring.

Interestingly, the additional momentum from the handstand appears to even out the length of the second flight significantly (see Figure 11). The end velocity of the standing back handspring is also much closer to that of the running back handspring. This means that the arms have almost completely compensated for the lack of a running start which is quite impressive.

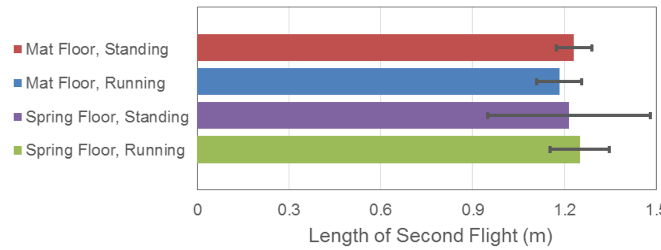

Figure 11: The length of the second flight, or the travel distance between the wrists in the handstand and the ankles in the final landing. Surprisingly, these values are not distinguishable even though the first flight lengths are very different. This along with the similar end velocities which can be seen in Figure 10 suggest that the pushing force from the arms almost completely compensates for the lack of a running start.

ANALYSIS OF THE HANDSTAND

Because the handstand appears to be the crucial phase that differentiates back handspring execution in different conditions, further study is desirable. Two key parameters, touch-off time and shoulder pushing displacement, were measured. However, it is hard to determine any trend from the results because there is a high level of uncertainty. The results are shown below for reference.

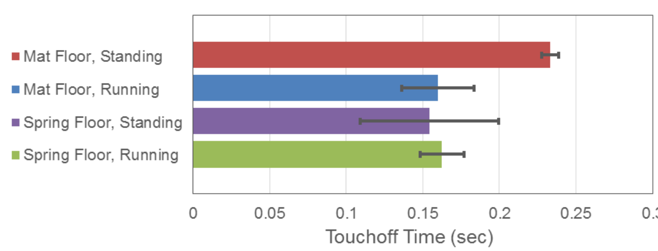

Figure 12: The time spent in the handstand based on six trials in each set of conditions. The longer duration of the handstand for a standing back handspring on mat floor implies that the impulse was spread out over time to reduce the force on the arms. However, the same cannot be said with confidence about the spring floor.

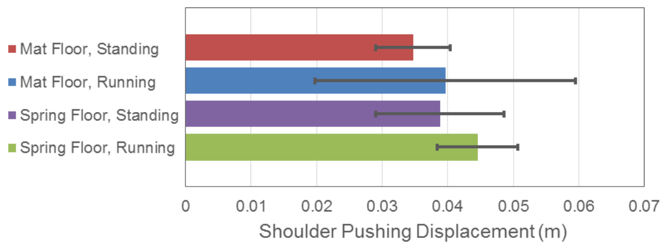

Figure 13: The shoulder pushing displacement, or the maximum change in arm length during the handstand. There is a high amount of uncertainty so no trends can be immediately determined.

The significantly longer duration of the handstand for a standing back handspring on mat floor is an embodiment of equation (1) because the impulse is spread over a longer time in order to reduce the force on the arms. However, it is hard to say if this is true for the spring floor as well. It is important to keep in mind that the shoulder location data is less reliable than the rest of the points. In order to do a full investigation of the handstand, more rigorous techniques are necessary.

One previous study also faced this problem of losing track of the shoulder marker. They compensated by attaching additional markers in the vicinity of the shoulder, drawn as the three white circles arranged in a triangle near the left shoulder. The blue markings are annotations that mark where the markers were placed in this experiment as a source for comparison.

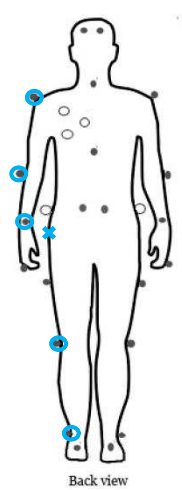

Figure 14: A diagram of the marker set used to follow the center of mass of a back handspring in [6]. The researchers compensated for the loss of their shoulder marker with three additional markers denoted by white circles arranged in a triangle by the left shoulder. The blue marks are annotations that show where the markers were placed in this experiment for comparison.

However, they used a 3D setup which could record those additional points while the possibilities in 2D are limited. There may be a way to extend the concept to 2D but there are fewer visible points that could be used for extrapolation.

Instead, it seems more reasonable to switch to a study of forces at this point. The magnitude of various forces are directly relevant to whether or not a tumbler will be able to finish the handstand, whereas calculations from these videos would be clouded by significant uncertainties. This may also increase the resolution of the touch-off time since when using video, ground contact is defined by an estimated threshold. Ideally, differences in floor type would also either present themselves or be determined irrelevant because by intuition, the spring floor would absorb and then reflect more energy than the mat floor, which would assist the arms in providing momentum to the back handspring. Thus, a force analysis would be the best next step to this investigation.

CONCLUSION

Because no change could be distinguished in most key parameters of back handsprings across floor surfaces and entry methods, it seems there are no tricks to achieving a back handspring by adjusting individual parameters. The challenge of supporting the forces must be taken up by the arms alone. However, a running back handspring is less demanding of additional momentum from the handstand, and since the key parameters are largely the same between running and standing back handsprings, new tumblers should learn the motion of a standing back handspring, but then focus on achieving a running back handspring first.

Interestingly, in the 2015-2016 school year, two of MIT's cheerleaders have already obtained their running back handsprings, and they were achieved before standing back handsprings. However, this was conditional on first having a good round-off to lead in, and many people still have work to do on their round-offs before they can reach this point. Nevertheless, if more understanding is desired about the back handspring itself, future researchers should turn to ground force analysis for new information.

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