OPTIMIZATION OF HANG-TIME TECHNIQUE FOR VOLLEYBALL SPIKE JUMPS

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In a previous study, we found that hang-time can have potential benefits on athlete performance during volleyball spikes, but hang-time usually comes at a cost of decreased peak height. To address this loss in peak height, we tested whether the trajectories of the "non-performing segments" (legs and non-hitting arm) can be modified to maximize the performance of the hitting arm without affecting the hang-time (defined by vertical motion of the head and trunk). The purpose of this study was to present details of an optimizer to facilitate a wide range of future studies aimed at maximizing performance. Using optimization we predict that for males the peak height of the hitting arm and its sagittal plane velocity at its peak can be increased by 52±11 mm ($p<0.001$) and 3.0±0.6 m/s ($p<0.001$) by modifying the trajectories of the non-hitting and hitting side legs respectively.

KEY WORDS: "hang", hang-time, optimization, hitting arm, trajectory, volleyball

INTRODUCTION: When athletes are in flight, the only force acting on them is the force of gravity. The center of mass (COM) of the athlete, like any other projectile, will follow a standard parabolic trajectory. If all body segments remain in a fixed configuration during flight (that is, if the body remains in a rigid position), then each of the body segments will follow the same parabolic trajectory. If, however, one or more segments move to follow a lower trajectory, other segments would also change relative position resulting in higher pathways so that their weighted sum, the COM, continues to follow the parabolic trajectory. This is the basic concept, the relative positioning of body segments, that allows athletes to "hang" in the air, or appear to pause their vertical movement near the peak of the jump. Visually, it appears to observers that the laws of physics are violated. However, by manipulating the relative position of limb segments, the athlete's trunk drops and then rises with respect to the whole body COM that is following a pre-determined parabolic trajectory, resulting in reduced vertical motion of the athlete's head and trunk. Note that the COM trajectory cannot be affected due to motion of the segments but rather it is the trajectory of head and trunk that changes. The flattened path of the head and trunk is perceived as "hang" (Gupta et al., 2015). In a previous study (preliminary description in Gupta et al., 2015), we studied the mechanisms behind "hang" and how it affects performance. We established that volleyball athletes (n=12) significantly increased ($p<0.001$) their hang-time when they flexed their knees and then extended them during flight compared to no flexion of the knees during flight. We measured hang-time as the time when the center of mass of the head and trunk combined had a near zero vertical velocity; mathematically, the time when the absolute value of vertical velocity of the center of mass of the head and trunk combined was lower than a threshhold minimum. Extended hang-time was shown to come at a cost of reduced peak height of the head and trunk. A critical finding in that study was that the athletes swung the hitting arm significantly later ($p<0.001$), with the hitting arm reaching its peak at 58.9% of flight duration when the athletes flexed their knees (and so extended their hang-time) compared to 50.7% flight duration when they did not flex their knees at all during flight. This suggests that athletes can use extra time in the air with a more stable head trajectory to adjust to different sets for the hit or to look at the opponents' defense and make decisions on how and where to hit.

These results raise an additional question. Since contacting the ball higher is an advantage in a spike, is there a way to compensate for the potential loss in peak height of the hitting arm during the hang-time? We hypothesize that the motion of the legs and non-hitting arm could be optimized without affecting the motion of body COM or hang-time (the motion of the head and trunk would remaining unchanged), while changing the motion of the hitting arm to obtain a higher arm swing. Overall, we are seeking a basis for maintaining the strategic and functional advantages of hang-time, but altering the trajectories of "non-performing segments" (legs and non-hitting arm) to positively affect the trajectory of the performing segment (hitting arm), compensating for the height lost during the "hang." The purpose of this study was to demonstrate an optimizer that can mathematically predict how athletes should change the motion of specific body segments like the non-hitting arm and legs such that key performance parameters like peak height of the hitting arm and the speed of the hitting arm can be optimized. This optimizer could allow coaches of any aerial sport skill to refine the performance parameters of their athletes. Below we present the optimizer and describe its application and results on jumps that showed extended hang-time, collected from 8 males. We conclude with recommendations on how this optimizer might be modified and improved.

METHODS: To accomplish our goal we designed a static optimization algorithm (optimization at each frame of the motion). We ran the optimization only during the hang-time period of the flight as we are specifically interested in optimizing hitting arm motion during this period. We calculated the COM of the hitting arm, non-hitting arm, and legs separately using the segmental method based on Zatsiorsky's model adjusted by de Leva (1996). For example, in order to see the effect of the non-hitting arm on the hitting arm, at each frame we shifted the COM of the non-hitting arm from -100 mm to 100 mm in steps of 5 mm in all 3 directions (vertical, M/L and A/P) (a total of 41 x 41 x 41 possible combinations) and calculated the resulting trajectory of the COM of the hitting arm for each combination, keeping the trajectories of all other segments and the whole body COM the same. While testing these possible combinations we maintained a constraint that the arms did not separate from the trunk (i.e., the distance between each arm COM and the respective shoulder joint center did not exceed the distance between these two points with the arm fully extended). Our goal was to find a movement pattern that maximizes both the height of the COM of the hitting arm and the absolute velocity of the COM of the hitting arm simultaneously. For this we defined a cost function which is the sum of the statistical measure (z scores) of these two variables (from the distribution of their values from all possible valid combinations). The cost function for all valid combinations of COM position for the frame being optimized was calculated and the combination that resulted in the maximum of this sum was chosen as the optimal solution. This solution resulted in a motion with high jerk (the time derivative of acceleration), particularly in A/P and M/L directions, since the jerk increased the absolute velocity of the hitting arm COM. (Note that velocity was calculated as finite differences of position values between consecutive frames, that is, subtracting the position of the COM of the hitting arm in the previous frame from its position in the frame being optimized. We started the optimization from the second frame of the hang-time period and kept the first frame the same as in the original trajectory.) To address the issue of jerk driving the determination of optimal trajectories we did three things. First, we added a constraint that, during the swing of the hitting arm, the A/P velocity of the hitting arm should only be anterior. The second adjustment was the addition of a check that the absolute value of velocity at each frame in each direction should not exceed twice the absolute value of maximum velocity in that direction in the original trajectory during hang-time. As a third modification we optimized the sagittal plane velocity and the vertical height of the hitting arm instead of its absolute velocity and vertical height. These three adjustments reduced the jerk in the optimized trajectory. A flow chart of the optimizer is provided in Figure 1.

The optimizer was applied to jumps from male participants in our previous study (preliminary description in Gupta et al., 2015) in which the athletes flexed their knees mid-flight and showed extended hang-time. These data were collected using a Vicon motion capture system in a lab where playing conditions were simulated by hanging a net, marking the center and attack lines and making the athletes hit a foam ball suspended at approximately 90% of the athlete's maximum vertical reach. We used the optimizer to predict the best possible trajectory of the non-hitting arm COM and each leg's COM. We used only the thigh and shank sub-segments of the legs. The non-hitting arm COM was varied by ±100 mm about the original trajectory in all three directions while the legs were varied by ±25 mm. This was done because, according to Zatsiorsky's adjusted model (de Leva, 1996), each leg (thigh and shank) weighs approximately 4 times as much as each arm and we wanted to give each non-performing segment an equal opportunity to affect the trajectory of the performing segment.

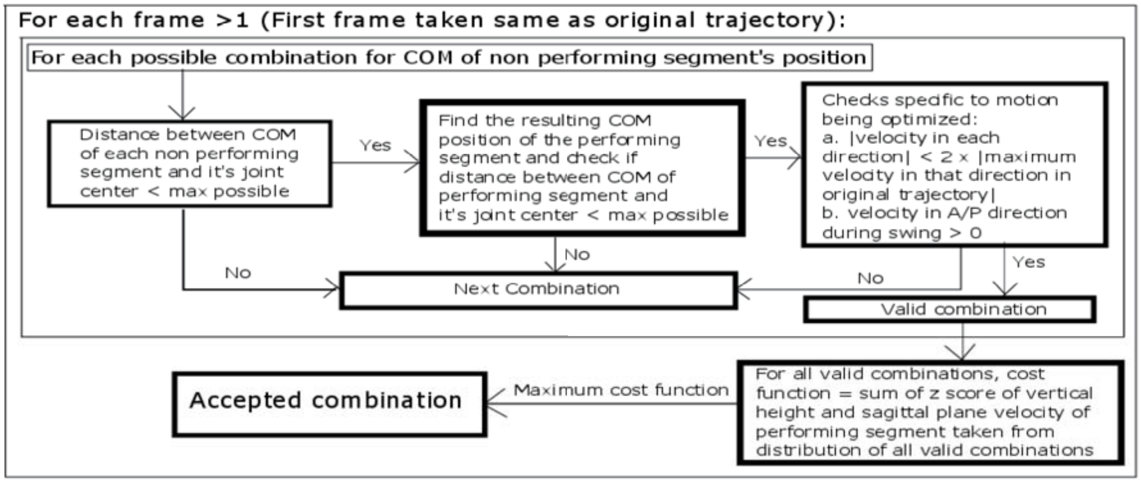

Figure 1: Flow chart of the optimizer

RESULTS:
Figure 2 shows the sagittal plane trajectory of the hitting arm COM when the non-hitting arm COM and each leg's COM trajectory were separately optimized for one jump. In the original trajectory, the hitting arm COM reached a peak height of 2569 ± 23 mm and corresponding sagittal plane velocity of 4.7 ± 0.5 m/s. We found that when optimizing the non-hitting arm COM, non-hitting side leg COM and hitting side leg COM, the peak hitting arm COM height increased by 52 ± 11 mm, 52 ± 11 mm and 31 ± 11 mm, respectively, and its sagittal plane velocity at these peaks increased by 1.7 ± 0.6 m/s, 1.4 ± 0.6 m/s and 3.0 ± 0.6 m/s, respectively. All gains were significant ($p<0.05$).

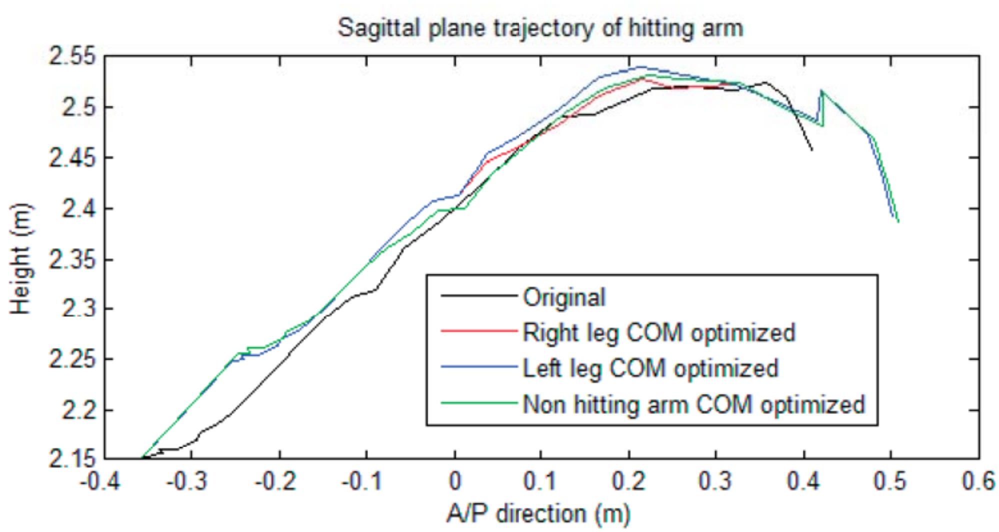

Figure 2: Sagittal plane trajectory of hitting arm COM when COM trajectories of other segments were optimized. (Note: 0 on A/P direction is the origin of the lab and not the frontal plane)

DISCUSSION: The optimizer yielded an improved trajectory of the non-performing segments to optimize the trajectory of the performing segment without affecting the hang-time across

all athletes. This finding provides evidence that the primary disadvantage of "hang" (a lower trajectory for the hitting arm) can be mitigated by altering the athlete's technique. An interesting result was that optimizing the non-hitting side leg COM trajectory increased the peak of hitting arm COM much less and its sagittal plane velocity at this peak much more compared to optimizing the hitting side leg COM or non-hitting arm COM trajectories. Future work will be directed at understanding the mechanisms behind these observed differences.
Although the optimizer was able to predict an optimized motion, the design of the optimizer is limited in the following ways. First, this optimization was based on changing the COM of the original trajectory of the non-performing segment within certain limits (e.g. ±100 mm for the non-hitting arm) and choosing the best possible valid solution. If the optimal trajectory is beyond this range, the optimizer would not find the best solution. A second limitation is that we optimized the sagittal plane velocity and the height of the hitting arm COM simultaneously instead of the absolute velocity and height (in order to address the jerk in the M/L direction). Also, we did not add any constraints for the M/L direction except for the maximum possible velocity. Limited constraints to control jerk could be the reason the optimized trajectories in the results were not perfectly smooth. Also, this could have caused the optimizer to find an anatomically impossible segmental configuration. For this static optimization, other methods such penalizing for jerk based on previous frames could be tried. Another way to address the unsteady motion could be to use musculoskeletal modelling and simulation to drive the optimized limb segment motions and test whether the optimized solution is anatomically feasible and can yield smooth force-length-velocity relationships. A third limitation is that this optimizer works on the COM of the segments (non-hitting arm, hitting arm and legs) and not on the sub-segments like the upper arm, forearm and hand for the arms. Hence the current study fails to directly address how the increase in the hitting arm COM performance parameters would translate to the hitting hand trajectory. Also, it is possible that the current setup might result in reduced elbow flexion just before swing. Hence, it will also be important when optimizing the trajectories of these sub-segments to add constraints on how the motion of sub-segments affects the COM of the whole segment. One way to perform these optimizations would be to design a global optimizer that first calculates all possible trajectories of the hitting arm during hang-time and then chooses the trajectory that maximizes vertical hitting height and absolute hand velocity at the maximum height and also controls the jerk cost of the entire trajectory simultaneously. However, this is computationally challenging and the use of optimization techniques other than brute force to span the solution space will need to be tested.

CONCLUSION: The purpose of this study was to introduce the design of an optimizer that can mathematically predict how athletes could change the motion of specific body segments such that the peak height of the hitting arm and the speed of the hitting arm can be maximized. The optimizer has the ability to introduce appropriate body-segment constraints and performance cost functions. For example, the cost function can be changed to give more weight to velocity than height for a particular athlete or hitting context, and thus is potentially applicable for improving the performance of a wide range of aerial sports. In the present study, we were able to suggest modified trajectories of the non-performing segments to enhance the performance of the performing segment without affecting the hang-time, thereby addressing the primary disadvantage of "hang" during a volleyball spike. This potentially can be a tool for coaches to suggest how their athletes could modify trajectories of their non-performing segments to maximize their spiking performance. This tool also has potential to be extended to maximize performance for any aerial sport skill.

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