ANALYSIS OF SIMULATED ANNEALING BASED OPTIMIZATION OF HUMAN MOVEMENT FOR PERFORMANCE ENHANCEMENT

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Technique is a defining feature of success in sport performance. In aerial phases of sport skills, in particular, it is the interplay among articulated body segments that optimizes the outcome. This interplay is characterized by intersegmental interactions during the projectile trajectory, the aerial phase, of the body's center of mass. The purpose of this study was to examine mathematical optimization approaches to finding the best balance of intersegmental interaction and in that process maximizing the desired performance outcome. We compared optimization using two different search algorithms, brute-force and simulated annealing and found that using simulated annealing is an efficient way to search for optimal solutions for biomechanical problems.

KEY WORDS: "hang", hang-time, optimization, simulated annealing, trajectory, volleyball

INTRODUCTION: During flight, the center of mass (COM) of an athlete follows a projectile trajectory which is dependent only on the take-off parameters of velocity, angle and height at take-off. In a majority of aerial sports, however, success in the task depends on the coordinated motion of body segments about the COM, not just on the COM trajectory. For example, in sports like volleyball and basketball, it is the variety of aerial manoeuvers that determine the outcome of the game. The height to which the COM will rise is determined by take-off velocity and angle. However, the height of a reach above the COM (e.g., release of the jump shot or contact of the ball in a volleyball spike) is dependent upon the configuration of body segments about the COM. Here we present a tool to mathematically optimize the trajectories of the body segments during flight such that a desired outcome parameter(s) can be optimized. The theoretical principle behind the function of this optimizer is that if the trajectory of one segment is changed, the trajectory of another segment or segments must also change in order to keep the total weighted sum of trajectories, the COM trajectory, unchanged. The optimizer creates multiple iterations and chooses the change that maximizes/minimizes the desired outcome parameter(s). The usefulness of such an optimizer lies in its ability to test the efficacy of changing movement pattern without time spent in practice or training as revealed by better approximation of the performance parameter(s). This tool also contributes to our understanding of intersegmental dynamics and the potential consequences of altering technique or equipment. The outcome parameter(s) may be technique specific and even individual specific.

Which search algorithm to employ in such an optimizer is a non-trivial problem. Numerous algorithms may be employed but they vary on resolution and computational demands. In this study, we compared the efficacy of two different search algorithms – brute-force and simulated annealing. We tested the methods on a specific sport application, the optimization of inter-segmental interaction during the hang-time period of a volleyball spike jump.

In a previous study on volleyball spike jumps (Gupta *et al.*, 2015) we found that flexion at the knees during the first half of the flight and knee extension in the second half of flight was associated with a reduction in the vertical motion of the head and trunk at the peak of the jump. This pattern of segmental action makes it appear that the athlete is hanging in the air for a prolonged period of time, rather than rising to a peak and immediately falling. The trajectory of the COM, in fact, remains unchanged, but the vertical motion of the head and trunk counterbalance the vertical segmental motion of the lower legs. Doing so, the head and trunk follow a lower and flatter peak trajectory and this is what we define as "hang". Hang-time provides potential benefits for successful performance. We found athletes swung significantly later ($p<0.001$) when they would "hang", meaning they had extra time with a stable head trajectory in flight to make decisions on how and where to attack or to accommodate difficult set trajectories. This prompted the performance question of whether there is a way to compensate for the potential loss in the hitting arm's peak height when an athlete “hangs” without giving up on the timing advantages of the “hang”. We used this performance analysis to assess suitability of brute force and simulated annealing methods.

METHODS: Data from 8 male and 5 female hitters who had played a minimum of National Collegiate Volleyball Federation (NCVF) division 1 were included. This optimization tool manipulates the trajectories of body segments without changing the trajectory of the COM. While doing so, it maximizes/ minimizes the chosen outcome parameter(s). This requires an appropriate cost function that mathematically represents the outcome parameter(s) and the definition of a search space, which defines the amount of change allowed in the trajectories of the segment(s). The definition of both cost function and search space can represent various constraints in the optimization problem. The constraints can be related to physiology, anatomy, mathematics or rules of sport. The optimizer searches through the search space and finds the changed motion of the segment(s) to maximize/minimize the cost function.
In order to explore the search space, we used multiple search algorithms. The correct choice of the search algorithm is critical for the success of the optimization, as it determines the computational complexity and usefulness of the optimizer. Brute-force is the most basic search algorithm; it determines the value of a cost function at every point in the search space. Although this approach promises to find the best solution, it is computationally demanding and fails if the search space is extremely large or has extremely high resolution. Simulated annealing is a smart search algorithm that stochastically searches the search space and reaches the global optimum with much higher computational efficiency. For this report, we used the simulated annealing code in MATLAB available under the global optimization toolbox release 2016b (The Mathworks Inc., Natick, Massachusetts, USA). This code starts with a given point in the search space and tests a random point around the current point and chooses that point as the next point if it is better (improves the value of cost function). It may also choose a point if it is worse than the current point based on a probability function. Choosing some points which are not better is an important feature to ensure an extensive search of the space. It then repeats this process with a smaller search radius. The algorithm avoids local optima by increasing the search radius once a specified number of points have been accepted. The algorithm runs until the change in cost function is less than the tolerance limit (established by the user). By this process, we end up choosing the global optimum more efficiently by searching less densely with respect to the whole space, and more densely around the optima.

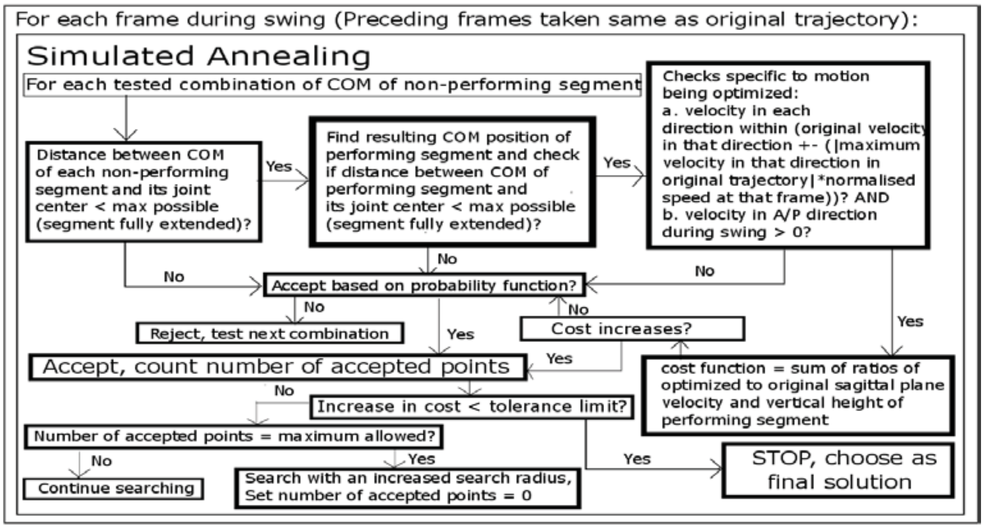

Figure 1: Flow chart of the optimizer

The formulation of the optimization was to change the trajectories of the COM of all the “non-performing” segments (both legs and non-hitting arm) and to allow those trajectory changes to be counterbalanced by the COM of the performing segment (hitting arm), such that the performance parameters of height and sagittal plane velocity of the performing segment (hitting arm) could be maximized. We did not change the trajectory of the head and trunk, as we wanted to preserve the potential benefits of “hang”, which are dependent only on the motion of the head and trunk. Gupta *et al.*, (2016) laid out an initial design of such an optimizer using a brute-force search algorithm. The brute-force search algorithm limited the capability of the optimizer to optimize only a single “non-performing” segment at a time. The computational complexity of brute-force searches increases exponentially as the number of variables to be optimized increases. This made the optimizer non-practical for application in situations where an analysis of multiple body segments is essential. For the current optimization, we employed a simulated annealing search algorithm. Figure 1 describes its flow and constraints. Optimizations were performed by changing each non-performing segment individually and also changing all three segments simultaneously. Hierarchical linear modelling was used to test the statistical significance of the results.

RESULTS:
Figure 2 gives a detailed description of the results of the optimization. Figure 2.c,d,e and f show that the optimized hitting arm trajectories were both higher and faster for both males and females compared to the non-optimized ones. Additionally, figures 2.b,c,d,e,f show that both brute-force and simulated annealing gave similar optimization results. However, the optimizer could not optimize all three non-performing segments simultaneously using the brute-force search algorithm, as the calculation was computationally too heavy. Figure 2.b. shows that the higher swings were still significantly later compared to the condition when the athletes did not “hang”. This emphasizes that even with the optimized trajectories, the athletes would have the additional time in the air with a stable head position to make decisions on where and how to hit. Figure 2.a. shows original and optimized trajectories of the COM of hitting arm of a jump from a randomly selected male during the hang-time period.

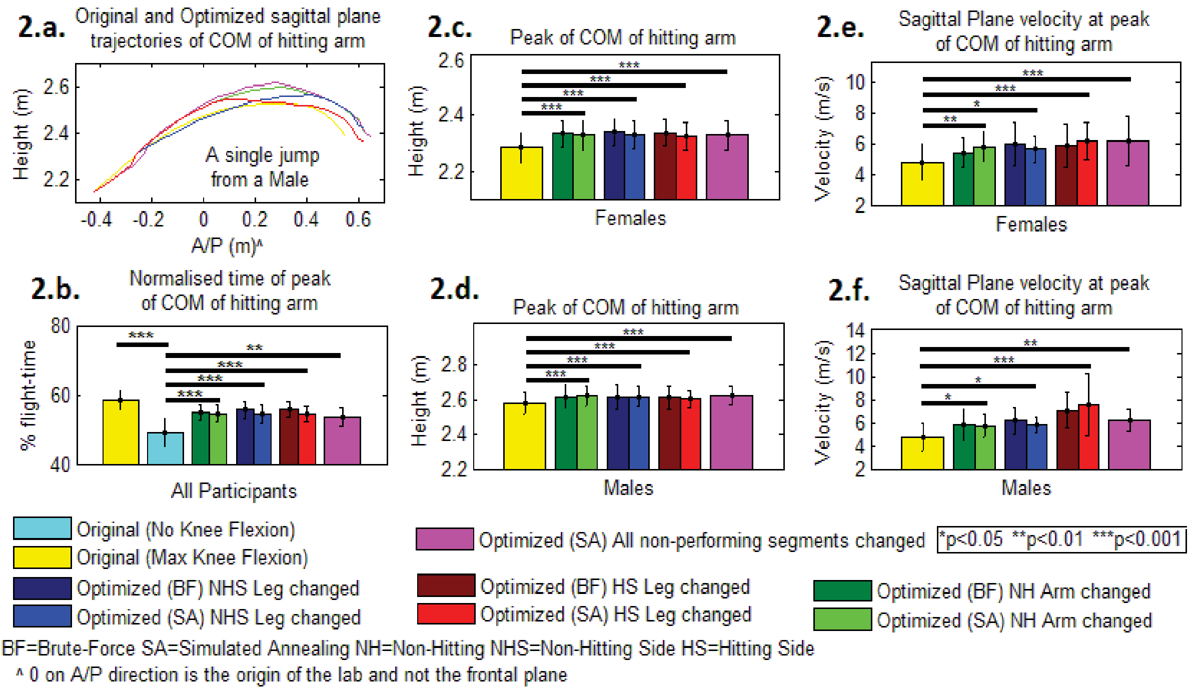

Figure 2: Detailed results of both brute-force and simulated annealing based optimizers.

Figure 3 compares the time taken by the optimizers. Note that the time taken increases in the brute-force search algorithm for optimizations when the trajectories of the legs COM was changed compared to the non-hitting arm because a finer grid search was required.

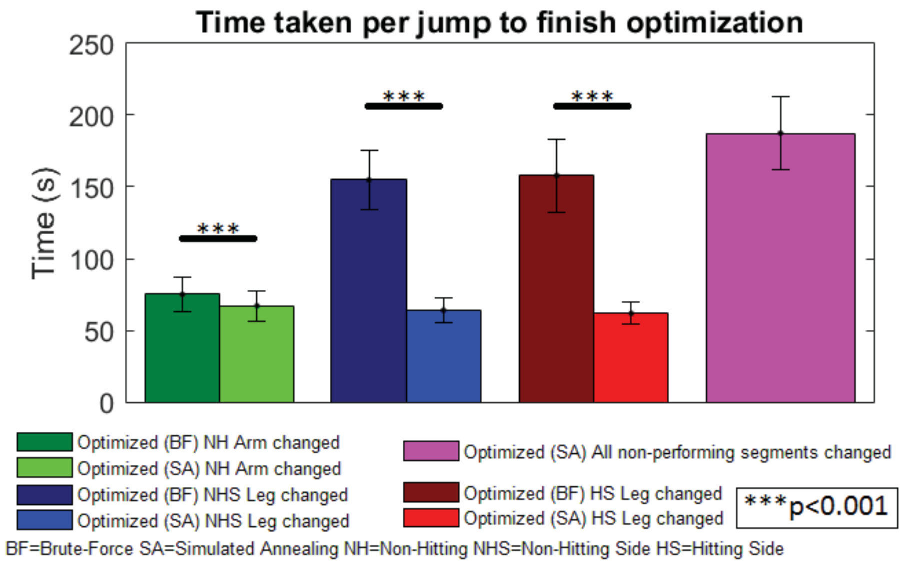

Figure 3: Time taken by each optimization process per jump

DISCUSSION: We describe the design of an optimizer that could be used by coaches and analysts of many aerial sports to maximize performance. Any performance parameter can be optimized by appropriate definition of a cost function and appropriate definitions of mathematical, physiological and anatomical constraints. This freedom of definition allows the optimizer to be both technique specific and athlete specific. We tested it to solve a biomechanical optimization problem that included both mathematical and anatomical constraints using both brute-force and simulated annealing search algorithms. We found that the results of optimization were very similar using either search algorithm but the time taken to perform the optimizations was drastically different. Moreover, the brute-force algorithm was unable to solve the higher dimensional optimization problem. This is because the number of points that brute-force tests increases exponentially as the number of dimensions of search space increases. This makes that optimizer highly impractical for sport skills that involve the analysis of multiple body segments, essentially a higher dimensional optimization problem. Even for the current optimization problem, the next step would be to optimize the motion of sub-segments (e.g. upper arm, forearm and hand) that could fit the optimized hitting arm COM trajectory. This next level of analysis induces a greater number of optimization parameters, more variables to optimize, and a greater number of anatomical and physiological constraints. Hence, the simulated annealing algorithm based optimizer is a more appropriate choice for solving these complex practical biomechanical problems than the brute-force based optimizer.

CONCLUSION: The purpose of this study was to demonstrate use of an optimizer that could solve biomechanical problems that are generally high dimensional and involve a variety of mathematical, anatomical and physiological constraints. We compared a simulated annealing based optimizer with a brute-force based optimizer to solve the same biomechanical problem and found that the simulated annealing optimizer could efficiently solve the high dimensional problem. This optimizer can be easily modified and used by coaches of any aerial sport for a variety of applications like performance enhancement by appropriate definition of the cost function and constraints.

REFERENCES:
Gupta, D., Jensen J.L. & Abraham, L.D. (2015). Biomechanical study of mid-flight body segment action and its effect on hang-time for volleyball spike jumps. *The 33rd International Conference on Biomechanics in Sports*. Open access

Gupta, D., Neptune R.R., Jensen J.L. & Abraham, L.D. (2016). Optimization of hang-time technique for volleyball spike jumps. *The 34th International Conference on Biomechanics in Sports*. Open access ../../AppData/Local/Temp/Temp1_files-2.zip/2/0