USE OF MUSCULOSKELETAL MODELING TO FIND THE BALANCE BETWEEN PERFORMANCE AND INJURY PREVENTION IN SPORTS – A PROOF OF CONCEPT

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In this study we used musculoskeletal modelling with mathematical optimization tools to find whole-body kinematics that simultaneously reduces risk of injury and enhances sports performance. Combining these objectives has long been the goal of sports science research. We focused on improving hang-time parameters in volleyball (Gupta *et al.*, 2015). We succeeded in preserving an advantage of hang-time (late swing) and address its disadvantage (potential loss in peak height of the hitting arm) by increasing the height of the hitting wrist by 1 cm, while at the same time not increasing the shoulder moments. This study provided a proof of concept that this optimization framework can potentially find a balance between performance and injury prevention in a complex sports task.

KEY WORDS: performance, injury prevention, simulation, optimization, volleyball

INTRODUCTION: Finding the whole body kinematic pattern that enhances performance with minimal risk of injury has long been the goal of research in biomechanics in sports. The human body is a multi-segment, multi-degree of freedom “machine” with complex connections between segments. Hence, both overall performance quality and injury in one segment could be due to the movement of a completely different segment, a segment that might not even be directly connected to the performing or injured segment. The majority of studies have focused on movement of one segment or the action of musculature around that segment to address the issues of performance and/or injury prevention (Reeser et al., 2010; Seminati *et al.*, 2013). Although these studies provide great insights, they provide incomplete causal information about the complex multi-segmental dynamics of movement tasks.

This information requires study of the full body during the task. *In-silico* simulations in conjunction with optimization methods have been used to identify whole-body kinematics for reducing peak valgus knee moments for side stepping task (Donnelly *et al.*, 2012) during the weight acceptance phase to prevent ACL injury. They used the open source musculoskeletal modelling software OpenSim (simtk.org.) to produce *in-silico* simulation of the movement pattern based on motion data. Residual reduction algorithm (RRA) is an optimization tool within OpenSim capable of altering the whole-body kinematics. This tool can be used through an outer level optimization process (Reinbolt *et al.*, 2011) to find a new movement pattern that reduces peak knee valgus moments and makes the simulations run with negligible residual forces and moments.

The outer level optimization (Reinbolt *et al.*, 2011) essentially works based on the definition of cost function that encapsulates the aims of the optimization process. Donnelly et al. (2012) used it to loosely follow the original movement pattern, reduce the residuals to near 0 and reduce the peak knee valgus moments. Since RRA within OpenSim allows for calculation of the whole-body kinematics and the corresponding joint torques, the outer level cost function

can be reprogramed such that it tries to enhance performance parameters and reduce injury risk factors like joint torques.

The purpose of the current study was to test this optimization framework on a sport application to find a kinematic pattern that not only helps prevent injury but also enhances performance parameters at the same time. Gupta *et al.* (2015) described the advantages and disadvantages of hang-time in volleyball. “Hang” is characterized by a plateau of the head and trunk (HAT) at the top of the flight, caused by flexion of knees during the first half of the flight and extension in the second. It was observed that volleyball players swung later (58.9% of flight-time) when they “hang” compared to 50.7% when they did not. This is advantageous, as it gives them extra time in the air to make decisions with a vertically stable head. “Hang”, however, comes with the disadvantage that the HAT does not reach the maximum possible height that it can without “hanging”. Hence “hang” is characterized by a stable, lower trajectory of the HAT that allows volleyball athletes to swing later. This lowering in HAT trajectory might also translate to a lowering in the hitting hand’s peak height. Hence the question arises whether there a way to address the loss in the hitting hand’s peak height, without losing any advantages of “hang”. Gupta *et al.* (2016) and Gupta *et al.* (2017) concluded that lowering the trajectory of non-hitting segments (non-hitting arm and legs) would cause an increase in the height of hitting arm’s trajectory. This allows the whole-body center of mass (COM_{wb}) to follow the same aerial trajectory. Gupta *et al.* (2016) and Gupta *et al.* (2017) succeeded in finding a higher trajectory of the center of mass of the hitting arm but failed to find the trajectories of the sub-segments of the hitting arm (upper arm, forearm and hand) and also failed to address whether their optimal trajectories would increase the shoulder torques, potentially causing an injury. Since OpenSim works with whole body kinematics and calculates joint torques, both these issues can be addressed. Specifically, we examined the use of outer level optimization (Reinbolt *et al.*, 2011) with the RRA tool of OpenSim to find optimal whole-body kinematics that 1) increase the height of the hitting hand, 2) minimize the shoulder torques, 3) maintain the hang-time, 4) do not change the trajectory of COM_{wb}, and 5) operate with negligible residual forces.

METHODS: We randomly selected a volleyball jump in which the athlete “hung”. The data for the jump were collected using a 10-camera motion capture system (Vicon Motion Systems, Oxford, UK). Within OpenSim we used a 14 segment, 37 degree of freedom (DoF) musculoskeletal model (Hamner *et al.*, 2010), scaled it to the participant and performed inverse kinematics during the hang-time period of the jump. This gave us the kinematics (i.e., generalized coordinates) for the model during the hang-time period. We followed the approach of Donnelly *et al.* (2012) for the optimization process. The first step was to create a nominal torque-driven simulation of the volleyball jump (i.e., a simulation that closely followed the experimental kinematics and operated with negligible residual forces). The outer level optimization tool adjusted the maximum allowable joint torques and the weight with which each generalized coordinate was tracked in the RRA tool. The cost function $J(x)$ it minimized in this step was as follows:

$$J(x) = \min_{x^R, x^T}\left[\sum_{i=1}^{n_q} w_{\ddot{q}_i}\left(\ddot{q}_i^{exp.} - \ddot{q}_i^{sim.}\right)^2 + \sum_{j=1}^{6} w_R\left(\frac{R_j\left(x_j^R\right)}{R_j^{max}}\right)^2 + \sum_{k=1}^{n_T}\left(\frac{T_k\left(x_k^T\right)}{T_k^{max}}\right)^2\right]$$

where, x^R and x^T are the excitation values for six residuals (R_j) and joint torques (T_k), and q_i are the generalized coordinates. The excitation values are the factor of maximum allowable force or torque that were used at any time in the simulation. This provided a mass adjusted model and optimized maximum allowable joint torques and their weights for the RRA tool. This step was run only from the start of the swing where the elbow started to go forward until the time of ball contact. We did not have force sensors on the ball, so the simulations were run only until ball contact. This limitation was deemed minor, since ball contact in vollyball usually happens after the hitting hand is at its peak because the athletes want to hit the ball down.

The next step was to generate an optimized simulation to increase the vertical height of the hitting wrist (1 DoF) while also reducing the shoulder joint moments (3 DoF: shoulder flexion, shoulder adduction and shoulder rotation). At the same time, keep the HAT kinematics (9 DoF) unchanged, since that is the segment on which "hang" is calculated and preserve the benefits of the "hang". We also did not want to change the trajectory of the COM_{wb} (3 DoF: x, y and z coordinates of the COM_{wb}) or have residual forces (6 DoF), as they represent external forces in the simulation which do not exist in reality. For the purpose of mathematical definition, the cost function tried to make the hitting wrist approach a height of 10 meters. The outer level optimization used for this step minimizes the cost function $J(x)$ written below:

$$J(x) = \min_{x^R, x^T}\Big[\sum_{h=1}^{9} w_{\ddot{q}_h}\left(\ddot{q}_h^{exp.} - \ddot{q}_h^{sim.}\right)^2 + \sum_{i=1}^{n_q-9} w_{\ddot{q}_i}\left(\ddot{q}_i^{exp.} - \ddot{q}_i^{sim.}\right)^2 + \sum_{j=1}^{6} w_R\left(\frac{R_j(x_j^R)}{R_j^{max}}\right)^2 + \sum_{s=1}^{3}\left(\frac{T_s(x_s^T)}{T_s^{max}}\right)^2 + \sum_{k=1}^{n_T-3}\left(\frac{T_k(x_k^T)}{T_k^{max}}\right)^2 + \sum_{wb=1}^{3} w_{wb}\left(p_{wb}^{exp.} - p_{wb}^{sim.}\right)^2 + w_w\left(10 - W^{sim.}\right)^2\Big]$$

where, p_{wb} is the position COM_{wb} and W is the vertical height of the hitting wrist. Since we wanted to allow the optimizer to change the kinematics of the body, other than the HAT kinematics, the errors in their tracking were weighted lower compared to other terms in the cost function. This step provided the desired optimal whole body kinematics. All computation was done through MATLAB (R2016b, The MathWorks Inc., Natick, MA, 2000) at the Texas Advanced Computing Center (TACC) at The University of Texas at Austin.

RESULTS:

Figure 1 shows that the optimized simulation (blue) of the jump reached higher than the nominal simulation (red) representing the original data, from two different views. We found that the hitting wrist reached 1 cm higher in the optimized simulation compared to the nominal simulation. Multiple small kinematic changes of the four segments were observed, but the most significant one was in the left hip flexion angle. The increase in the hitting wrist's height seems to be driven by the fact that the left hip flexion is 8.1° lower in the optimized simulation compared to the nominal simulation. The lower left hip flexion caused the center of mass of the left leg to be 7.9 mm lower, allowing the lighter hitting arm to reach higher without changing the COM_{wb}. From the nominal to optimized simulations, the peak shoulder flexion, adduction and rotation moments changed from -18.606 Nm to -18.574 Nm, from 8.045 Nm to 8.126 Nm, and from 10.298 Nm to 10.056 Nm, respectively. The average residuals in both simulations were negligible (less than 2 N for residual forces and less than 5 Nm for residual moments). The average difference in HAT kinematics was less than 1° for angles and less than 5 mm for position between the two simulations. The average difference in COM_{wb} position was less than 0.2 mm between the two simulations. The peak height of the hitting hand wrist in the nominal simulation was at 53.2% flight-time and 54.2% flight-time in the optimized simulation. Hence, the primary advantage of the "hang" (later swing-time) was preserved.

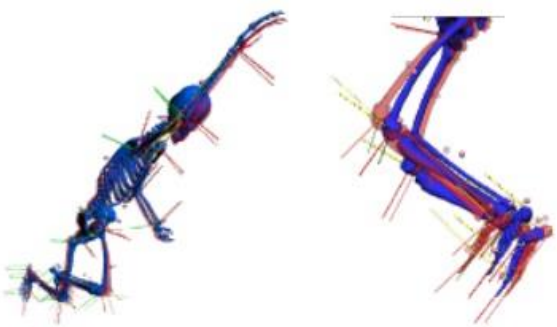

Figure 1: Top and left side views comparing nominal simulation kinematics (red) with the optimized kinematics (blue).

DISCUSSION: We attempted to find a whole-body kinematics pattern that increased the height of the hitting wrist by changing the kinematics of the four extremities and not the head and trunk. At the same time, we attempted to minimize the shoulder torques and not change the trajectory of the COM_{wb}. The peak height of the hitting wrist increased by 1 cm while still maintaining the hang-time by not changing the HAT and COM_{wb} trajectories or increasing the peak shoulder torques. Although further refinement of the cost function may lead to better results, these results provide a proof of concept that musculoskeletal modelling combined with dynamic optimization can be used to attain a balance between performance and injury prevention. In addition, since OpenSim calculates kinematics of the whole body, we can add terms in the cost function of the outer level optimization to control the velocity of individual segments. For example, in the current volleyball movement, we can further pursue minimizing injuries by reducing shoulder joint angular velocities while simultaneously enhancing performance by increasing hitting wrist velocity.

It is important to note that we used a musculoskeletal model (Hamner *et al.*, 2010) that does not contain all the constraints of the complex shoulder joint. In future work, we shall use more complex models like the scapulothoracic joint model (Seth *et al.*, 2015) that is designed for the complex shoulder joint. The use of a simpler model, however, does not affect the validity of the proof of concept for which this study was designed. The wide variety of parameters that OpenSim calculates that can be controlled through optimization methods makes this a promising method for a wide variety of sports biomechanics applications.

CONCLUSION: This study provides proof of concept that musculoskeletal modelling in conjunction with optimization methods can be used to attain an optimized balance between performance and injury prevention. A complex biomechanical problem for the sport of volleyball was solved, and optimal kinematics were attained that enhanced performance without increasing risk of injury. A simulation-based approach such as this provides a promising method for solving simultaneously complex biomechanics problems from the points of view of performance, injury prevention and other required or desired constraints.

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