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Application of Induced Acceleration Analysis and Computer Simulation in Sports

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The purpose of this work is to use two examples to illustrate how forward dynamics formulations can be used to evaluate and enhance sports performance. In a baseball pitching study, induced accelerations were uses to determine that centripetal/coriolis effects along with shoulder and elbow moments made the largest contribution to ball velocity. In a figure skating project computer simulations were used to enhance the ability of skaters and coaches to explore different performance strategies during the flight phase of a figure skating jumps. Specifically computer simulation software was developed to provide insight into technical modifications necessary to produce meaningful improvements in performance. Once an improved movement pattern was identified, the skater returned to their home arenas to work on implementing this new pattern.

KEY WORDS: Induced Acceleration, computer simulation, forward dynamics.

The purpose of this manuscript is to illustrate how forward dynamics formulations can be used to evaluate and enhance sports performance. Specifically we will give one example of how induced acceleration can be used to better understand of a baseball pitch and one example of how computer simulation can be used to improve performance of world class figure skaters.

Induced Acceleration Example: Sources of forward ball velocity in a picthed baseball

During a baseball pitch, the dependence of ball velocity on muscle/joint actions has been inferred (Toyoshima, Hoshikawa, Miyashita & Oguri, 1974; Stodden, Fleisig, McLean & Andrew, 2005), but not measured directly. Recent advances (Goldberg, Anderson, Pandy & Delp, 2004) in musculoskeletal modeling have included the development of techniques that can directly determine the contribution of muscle groups to joint or segment velocities associated with locomotion. This approach (induced velocity analysis) is ideal for studying whole body and upper extremity motions where there is an easily measured goal, such as maximizing ball velocity during pitching. Our purpose was to study high level adolescent pitchers to determine how joint torques, gravity and velocity effects contribute to the forward velocity of a baseball at release.

Kinematic and kinetic data were collected from six elite high school male baseball pitchers (mean height = 1.86m, mean weight = 83.9kg) who had no history of arm injury and were able to throw at least 80 mph under game conditions. During testing the subjects threw a straight overhand pitch from the windup on flat ground. Data were collected using a 7-camera Vicon motion capture system (250 Hz) and three AMTI force platforms (1000 Hz). One representative pitch per subject was analyzed from the last instant of zero ball velocity to ball release.

The 14 segment biomechanical model included feet, legs, thighs, a pelvis, a combined thorax-abdomen-head, arms, forearms and hands. Visual3D software (C-Motion, Inc.) computed the kinematics and kinetic input for the model. At each video sample, the model was positioned based on the kinematic data. Gravity and all velocities were set to zero. The joint torques were turned on, one at a time, to determine the forward acceleration imparted on the ball by that torque (induced acceleration). The forward acceleration due to gravity

was determined by setting all torques to zero and setting gravity to 9.81 m/s^2. Finally, the centripetal/coriolis effects were determined by setting all torques and gravity to zero and driving the model using the velocities as measured by the motion capture system.
The induced velocity from each source was obtained by calculating the area under each induced acceleration curves. The model was validated by comparing the total induced velocity of the ball computed by the model with the forward velocity of the ball obtained from a radar gun.
Net ball velocity at release determined by the model was 64.5 mph, which was comparable to that recorded by the radar gun (73.8 mph). The induced velocity analysis (Table 1) indicated that acceleration produced by the velocity of the segments (centripetal/coriolis), made the largest contribution to ball velocity (57.8%). The pitching shoulder was found to generate forward ball velocity (31.0%) in the period of rapid acceleration just prior to release while the elbow torque tended to increase forward velocity (18.1%) during cocking phase of the pitch. Gravity, the lower extremity joint moments, and wrist joint moment made either small or negative direct contributions to ball velocity.
Toyoshima et al. (1974) inferred that the trunk and lower extremity accounted for almost 50% of ball velocity, whereas Stodden et al. (2001, 2005) concluded that ball velocity increased with increases in elbow flexion torque, elbow and shoulder joint forces, and increases in pelvic and upper torso velocity. Results from the induced velocity analysis indicate that the largest contributions came from the centripetal and coriolis effects. The study also found that the lower extremities were unlikely to make a direct contribution to ball velocity while the muscles crossing the shoulder and elbow did indeed make significant contributions.

Table 1
Mean (n=6) sources of ball velocity as percentages of total induced forward velocities.

	lower extremities	waist	shoulder	elbow	wrist	gravity	centripetal/ coriolis
Mean%	-1.3	1.3	31.0	18.1	-6.9	0.0	57.8

Computer Simulation Example: Simulation of the Flight Phase of Figure Skating Jump

The skater's objective when performing multiple revolution jumps is to complete enough rotations in the air to enable them to land under control in the required position. King, Arnold A & Smith (1994) found that achieving high in-flight rotational velocity was due to the ability to generate angular momentum at takeoff and minimize the momentum of inertia during flight. Johnson and King (2001) found that one of the differences between successful triple and quadruple revolution jumps was the skaters' ability to decrease the in-flight moment of inertia and increase maximum rotation speed. The ability to optimize in-flight position would be a tremendous aid to skaters attempting to land difficult triple and quadruple jumps. One way to enable a skater to optimize in-flight position is through simulation. Yeadon (1990) and Yeadon, Atha & Hales (1990) demonstrated how computer models and simulation software can used to successfully train competitive athletes to optimize their in-flight movement patterns.
The goal of this project is to enhance the ability of skaters and coaches to explore different performance strategies during the flight phase of a figure skating jumps. Specifically we

have been developing simulation software to provide informative insights into technical modifications necessary to produce meaningful improvements in performance. These simulations enables skaters and coaches to assess the effects of modifying the position of body segments on performance, and provides the skaters and coaches with the ability to develop strategies for improving performance.

To date, data were captured on 29 world and national senior and junior class skaters using a 10 camera Motion Analysis (Santa Rosa, CA USA) motion capture system mounted to aluminum camera support structures installed in the ice arena surrounding a collection volume with approximate dimensions of 8m x 9m. The motion capture data were sampled at 240 Hz. Data was analyzed only for the flight phase of the jump.

Fifteen anatomical segments were used in the model with thirty six targets placed on the subject to calibrate the markers to the underlying skeletal structure. The data from the skating jumps imported into Visual3d software (C-Motion, Inc, Germantown, MD USA). Visual3d used an Inverse Kinematics (IK) approach (Lu and O'Connor, 1999) to compute the position and orientation of the segments during the jump. The inverse kinematics approach was used because it was believed that adding the joint constraints could reduce the effect of measurement and soft-tissue error and provide mechanical consistency between the kinematics and the forward dynamics models used in this study.

Once Visual3d completed the IK a separate software application preformed the simulations of the figure skating jumps. The software attempted to recreate the jump using a forward dynamics model. In the forward dynamics model the pelvis was the root segment free to move relative to ground and the joint constraints matched those of the Visual3d IK model. The initial conditions (the root position and velocity as well as the position and velocity of the joints) were obtained from the motion capture data. Starting from the initial conditions, the joint motions were driven using the motion capture accelerations while the motion of root (pelvis) segment was governed by the conversation of angular momentum. SD/fast software (PTC, Inc, Needham, MA USA) was used to perform the forward simulation. If the kinematic data were perfect and the segments properties perfectly represented the individual, then simulation would be expected to match the motion capture data. However, imperfections in the motion capture data and in the model properties produced errors that resulted in differences between the simulated and measured movements. These errors also manifested themselves in the motion capture kinematics where it was observed that the angular momentum was not conserved throughout flight. To solve this problem, we decided to optimize the initial velocity of the root segment to obtain the best match between the motion capture and simulated data at 33%, 66% and 100% of the motion. The optimization was performed via a Levenberg-Marqaurdt non-linear optimizer (MINPACK).

Once the optimal initial conditions were obtained and we were confident that our simulations were a good match to the motion capture data, the skater and coach could then change the kinematics of any of the joints during subsequent simulations and attempt to increase the number of revolutions in the air. This gave the coaches and skaters the ability to develop strategies for improving performance without having the skaters repeatedly jump on the ice. The software (Figure 2) allows the skaters and coaches to manipulate the skaters in air position at the computer which enables them to search for the most promising areas of improvements while minimizes the number of jumps the skaters must perform on ice. The simulations also indicated whether skaters possessed the theoretical ability to increase their spin by enough revolutions to complete the required jump. In some instances, the simulations were also used to help the coaches and skaters determine which jumps the skaters were most likely to successfully land and thus add those jumps to their competitive programs.

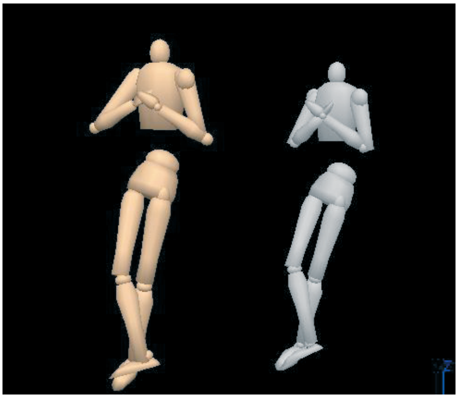

Figure 2: The Optimization page of the SkateModel program, showing the agreement, between the motion capture model and the simulated model just prior to landing.

Once a theoretically improved movement pattern was found, the skater returned to their home arenas to work on implementing this new pattern. The first skater tested was local and reported in an interview to the New York Times "I focused on keeping my elbow down, and my landings were a lot more solid," she "It definitely proved itself." Since that initial session almost 30 national and world class US skaters have undergone simulation sessions. This spring two male skaters were able to implement their training recommendations within one week of a simulation test session and completed their first ever quadruple jumps while one female skate completed her first ever triple axel.

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