Validating a Solid-Static Single-Armed Male Prototype Tasked to Produce Dynamic Movement from the Shoulder Through the Preparation Phase

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Abstract*— The purpose of this study was to design, implement, and validate a methodology to determine baseline measures during the preparation phase (PREP) of seated weight-bearing locomotion. In order to evaluate this methodology this study investigated the external movement produced by the shoulder joint-centre of the upper limb through a seated downward poling motion. A solid-static anatomically correct prototype was designed to produce isolated dynamic movement about a human's shoulder joint-centre; this particular investigation replicated the average male weighing 80kg having fixed elbow (135°) and wrist-stick (45°) angles, and dynamic shoulder start angles (-10°, 0° and +10° to the horizon). The prototype was tasked to produce PREP; a phase identified in seated locomotion produced through a double poling fashion. Trajectory and reaction forces created through PREP were evaluated using a standard Newton-Euler mathematical model in conjunction with a 3-dimensional motion capture system and force plate. Trajectory data concluded that the prototype was of reliable and valid mechanical design producing near identical curves for all trials individually as well as combined averages. Evidence also indicated that all trials displayed similar reaction forces, which produced torque in an anticlockwise direction about the shoulder. Since the prototype is solid and designed to mimic the male upper limb data can be used to describe minimal reaction forces onto the shoulder joint produced from PREP. Understanding external forces at baseline measures allows for valid assumptions to be made or dismissed concerning internal forces within the human body. Dynamic biomechanical analysis requires assumptions involving internal and external parameters when producing a movement. The addition of PREP to the seated propulsion cycle is unclear identifying the need to investigate the biomechanics produced through this phase; full arm extension to pick-plant. This study has developed an improved model of the upper limb during seated double poling.

***Keywords*— gait, preparation phase, shoulder, double poling, sledge hockey.**

I. INTRODUCTION

Locomotion produced by the shoulder joint in an upright double poling fashion promotes the use of two phases: 1) the contact phase known as *propulsion*, and 2) the return phase of the cycle known as *recovery* [1]. Locomotion produced by the shoulder joint in a seated double poling fashion promotes the use of a third phase, *preparation* [2-3]. This phase's location is dependent upon pole length. For shorter pole lengths preparation occurs from full arm extension to pick-plant (sledge hockey) compared to extremely longer pole lengths where preparation occurs from pick-off to initiation of return of the forward cycle (cross country sit-skiing) [2-3]. Due to changes in sledge movement in conjunction with observable biomechanical trends investigation involving the integration of the preparation phase within the poling cycle for seated locomotion is warranted; however, currently the direct benefit of this additional phase is unclear to the overall biomechanics of the complete cycle [2-3].

Daily locomotion for seated shoulder dependent populations is usually produced from the arms pushing in a forward cyclical pattern possibly assisted by short poles during difficult terrain or used to produce elevated velocities; this cycle is commonly seen in para-sports like sledge hockey [2-4]. This study developed an anatomically correct solid-static prototype mimicking the upper body of a single armed average adult male holding a sledge hockey stick; the shoulder joint producing the only dynamic movement (Fig 1) [5-7]. Addition of the shortened poles to this cycle allows for impact reaction forces to be evaluated from a focal point; pick-plant. By isolating the shoulder joint analysis of the reaction forces caused by pick-plant can be evaluated and used to determine the importance preparation has to the cycle. Due to the architectural design of the prototype baseline measures can be determined concerning the minimum reaction forces caused by this phase. Ongoing research involves investigating the dynamic start angles in combination with various fixed elbow and stick-wrist angles to assist in developing baseline measures of a male arm during the preparation phase of seated weight-bearing locomotion.

Understanding external forces at baseline measures improves assumptions made about the internal forces acting within the human body. Dynamic biomechanical analysis requires assumptions to be made about internal and external parameters when producing a movement. Evidence collected will provide future research with a heightened level of confidence concerning assumptions of the human upper limb in a downward motion. The purpose of this study was

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Fig. 1. An illustration of the anatomically correct average adult male wood prototype designed to investigate the preparation phase for shoulder joint produced seated locomotion (not test position).

to design, implement, and validate a wooden prototype in order to investigate the preparation phase during seated weight-bearing locomotion produced by the shoulder using Newton-Euler relationships through 3-dimensional motion analysis.

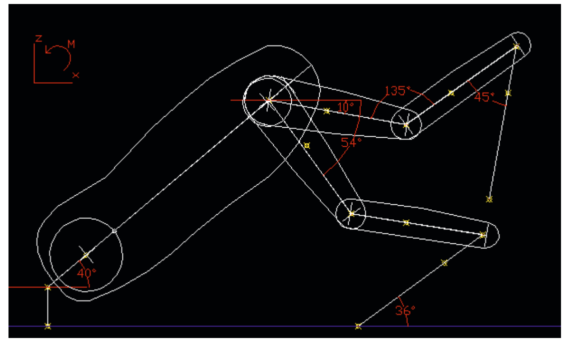
II. METHODOLOGY

Architecture for the prototype incorporated US Marine Corp male personnel data with previously defined anthropometric parameters such as shape, length and mass of segment (Fig 2); average adult male body-weight (BW) was determined to be 80kg [5-7].

A. Mathematical Model

A mathematical model was developed using standard inverse-dynamic equations for the prototype indicating that all reaction forces are transferred back to the shoulder joint with fixed joint angles at the elbow (Ψ) and wrist-stick (γ), as well as dynamic shoulder start angle (β_0) from the horizon (Fig 2) [5-8]. These values were used to determine the torque (τ) at the shoulder, angular rate (velocity (ω) and acceleration (α)), inertia (I) and linear acceleration (a_x and a_z) for each segment's centre of gravity (CoG), and pick-plant angle (η_f). From a pilot study investigating the movement of a task-naïve male participant, preparation was determined to last 0.16s and pick-plant reaction forces to be about 15·BW [8].

Using investigations evaluating sit-ski CoG, inertia, and double poling biomechanics variations of fixed and dynamic upper limb joint angles were used in conjunction with a motion capture system to test and verify the prototype [1-3,8]. Angle combinations included β_0 at 10°, 0° and -10° used in conjunction with Ψ at 135° and γ at 45°. Note: Additional testing investigating Ψ at 120° and 150°, and γ at 30°



Fixed Angles: Λ=40° (hip), Ψ=135° (elbow) and γ=45° (wrist-stick)
Dynamic Angles: β_i (shoulder) and η_f=36° (pick-plant)

Fig. 2. An illustration of the mechanical parameters determined from the mathematical model for the anatomically correct average adult male prototype [2-3,5-8].

is currently being implemented. Three useable trials were collected for each combination and averaged.

B. Physical Model

The prototype was fastened to a sledge hockey sledge with fixed hip angle Λ=40° from the horizon and weights placed in the bucket to off-set the balance allowing free stance; a velcro strap was attached to the forearm's CoG and raised to where the neck would be located, then released allowing the arm to drop down and pick to contact the force plate. Two plastic washers 4.00cm in diameter were used to decrease friction at the dynamic joint. Two 1.30kg wrist-weights were attached to the upper arm in a stretched out fashion (lateral and medial) with an overlap at CoG mimicking arm morphology. A 1.20kg ankle-weight was attached to the lateral forearm in a stretched out fashion (Fig 1). Markers were placed at the joint-centre for the shoulder and elbow, upper arm CoG, forearm CoG, anterior wrist, posterior wrist, and blade, joint and pick of the stick. Additional markers were used to construct the torso and indicate the left superior anterior and posterior hip; markers were 14mm in diameter.

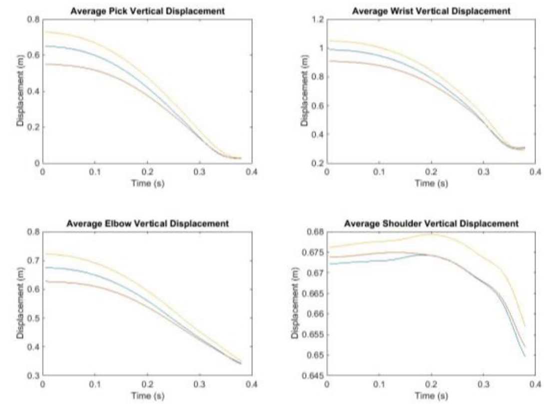
A Vicon 3-dimensional motion analysis system was used along with a Kistler force-plate; data were collected at 200Hz and 1000Hz respectively. MATLab code was written for both trajectory and the force plate data using a zero-lag fourth-order Butterworth lowpass filter at 12Hz and zero-lag second-order Butterworth highpass filter at 4Hz, respectively.

Kinematic data was collected and analyzed for the period of 0.38s pre contact to the initiation of stick recoil (Fig 3 & 4), and ground reaction force data was collected and analyzed for a period of 26ms, initial pick contact to initiation of stick recoil as peak impact forces are generated in within this period (Fig 5). Validation for investigation durations were developed from the notion that gravitational pull increases velocity over time and the simple biomechanics which occur during the contact phase in the stroking cycle; the pick would not be able to bounce post impact.

III. Results

Trajectory data outlining the preparation phase for the joints and pick were plotted individually for each start angle then averaged between trials and finally as a combined trajectory. Kinematic data illustrated vertical displacement trajectories of approximately 0.18m for the pick, 0.15m for the wrist and 0.09m for the elbow. Shoulder joint-centre was a local origin and the point of rotation, however, vertical displacement was investigated to prove mechanical reliability indicating that on average the shoulder vertically displaced approximately 0.23cm and was also the only focal point that showed an increase in deviation as β_0 decreased. Horizontal trajectory for all β_0 illustrated near identical curves for each trial of the pick, wrist and elbow. Again, investigating mechanical testability a slight deviation was observed from the shoulder throughout the phase (< 5.0mm). Mediolateral trajectories for all β_0 illustrated similar curves for each trial with the pick, wrist and elbow. A slightly greater deviation was seen from the shoulder throughout the phase (< 30mm). Vertical trajectory for all β_0 illustrated similar curves for each trial with the pick, wrist and elbow depicting near identical curves. Minute deviation was observed once again from shoulder throughout the phase (< 10mm). Figure 3 illustrates the average vertical displacement of the three start angles; initial deviation is to be expected as start height lowers as the angle is decreased to/past the horizon. Figure 4 illustrates the average displacement for each β_0 and the combined trajectories for the pick, wrist and elbow with the shoulder represented as a local origin through 3 dimensions. Again, the illustrations produced near identical motion trajectories for their respective joint/pick direction; individual through to combined average.

Pick-plant peak vertical reaction force was illustrated prior to 5.0×10^{-3}s for all trials. Figure 5 illustrates the reaction forces for all trials; no average was plotted due to the large deviations between trials. Reaction forces have a negative orientation within their respected illustrations to assist with a visual connection to an increasing force (more negative) from a downward motion. Further investigation regarding ground reaction forces is warranted, however, for validation purposes Figure 5 portrays an ideal trend for each reaction force. Combined average peak reaction force for mediolateral force was determined to be 103N, horizontal force 897N and vertical force 687N. Unlike, the mathematical model horizontal force produced the greatest amount of force onto the shoulder joint.



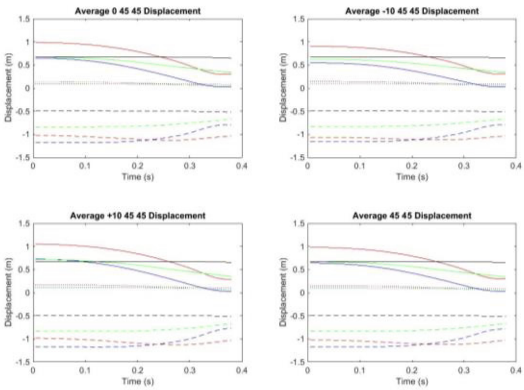
β_0 = +10° (yellow), β_0 = 0° (blue), β_0 = +10° (red)

Fig. 3. An illustration of the three start angles' average vertical trajectories for the pick, wrist, elbow and the local origin; the shoulder; β_0 at 0°, +10° and -10°. Deviation in start height was to be expected due to the start angles.

IV. Discussion

Comparing Figures 3 and 4 confidence in mechanical production from the prototype can be concluded. Deviations are a result of start height and minimal, which do not affect the curve created by the data. Since each trial produced near identical trajectories compared to the average of all three start angles this prototype has mechanical testability. Reaction forces displayed in Figure 5 also concludes that the mechanical output from this prototype is valid and reliable. Limitations of the prototype design include but are not limited to: offsetting weight within the bucket to promote free stance; the torso not weighing the appropriate 0.63BW as a human does, affecting shoulder displacement. Ideally the shoulder joint-centre should remain static, however, without the additional weight of the torso deviation from the desired path occurred at this point of rotation; this was exhibited from the reaction forces produced by the system as well as trajectory data. Finally, minimizing the vibration effect from pick-plant to secure the pick to the ground upon impact. Reactions forces were lost due to this limitation. Further investigation at this point of contact is required.

Finally, validation from the mathematical model indicated that from averaged (x,z) data net force onto the shoulder was approximately 1109N where horizontal force equaled 444N and vertical force 1016N at average pick-plant (67°). Experimental averaged (x,z) data indicated net reaction force of 1130N; 98% force transfer compared to the



Pick (blue), Wrist (red), Elbow (green), Local Origin: Shoulder (black), Vertical Trajectory (-), Horizontal Trajectory (--), Mediolateral Trajectory (..)

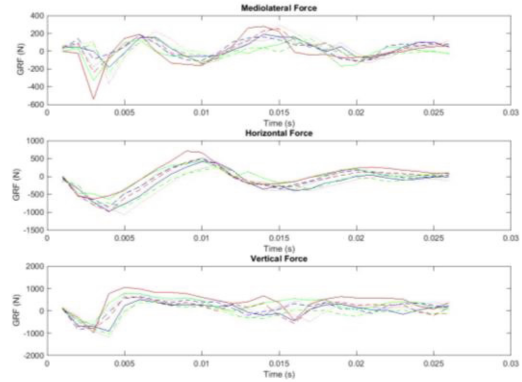
Fig. 4. An illustration of the average of the three start angle trajectories for the pick, wrist and elbow with a local origin at the shoulder, and a combined average. Near identical curves were observed for all individual and combined data.

100% force transfer determined by the theoretical data or 1.9% percent difference of transferred force. Comparing the theoretical data with experimental data this study concludes that testability exists for the methodology developed to determine baseline measures of the preparation phase for seated weight-bearing locomotion. From the mechanical function of the prototype through the preparation phase baseline measures can be determined and used to assist in the investigation of seated locomotion produced by the human shoulder joint. Specifically, internal upper limb forces can be compared to baseline measures either promoting or dismissing the assumption required. As more data is acquired using various elbow and wrist-stick angles evidence can allow for in depth investigation at desired locations throughout the phase proving or disproving the integration of this phase to the complete cycle.

Additional benefits obtained from comparing baseline measures to human produced biomechanics for this specific movement can be awarded to shoulder dependent daily living populations. Data can bring awareness to the amount of repetitive force being transferred back to this load bearing joint during daily tasks. Increased joint structure would be the ultimate goal as the shoulder joint was mechanically designed for the largest range of motion in the human body and not as a primary load bearing locomotor like the hip.

IV. Conclusion

In conclusion, this study confirms that theoretical and experimental results prove mechanical testability of the prototype, validating it for future research to define baseline



$\beta_0 = +10^o$ (--) $\beta_0 = 0^o$ (-) $\beta_0 = +10^o$ (..), Trial 1 (blue), Trial 2 (green), Trial 3 (red)

Fig. 5. An illustration of reaction forces produced from the three start angles throughout the three co-ordinate planes.

measures of the preparation phase for seated weight-bearing locomotion produced by a shoulder joint.

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