# Muscle Force Transmission to Operational Space Accelerations During Elite Golf Swings*

Emel Demircan[1], Thor F. Besier[2] and Oussama Khatib[1]

*Abstract*— **The paper investigates the dynamic characteristics that shape human skills using the task-space methods found in robotics research. It is driven by the hypothesis that each subject's physiology can be reflected to the task dynamics using the operational space acceleration characteristics and that elite performers achieve the optimum transmission from their available muscle induced torque capacity to the desired task in goal oriented dynamic skills. The methodology is presented along with the full body human musculoskeletal model used for the task-based analyzes. The robotics approach for human motion characterization is demonstrated in the biomechanical analysis of an elite golf swing. This approach allows us to trace the acceleration capacities in a given subject's task space. The results of the motion characterization show that humans in fact follow a path of trajectory in line with the maximum available operational space accelerations benefiting from their physiology shaped by the combination of the force generating capacities of the muscles as well as by the joint and limb mechanics.**

## I. INTRODUCTION

Understanding the physio-mechanical properties of human motions can significantly improve our ability to prevent and cure motor diseases and disabilities that affect large numbers of people. Analyzing a subject's motion is a challenging process that requires tools such as physics, bio computation, imaging techniques, computer simulations and robotics. Together they are in the pursuit for addressing this challenge in the study of biomechanics. Biomechanics researchers aim to analyze movement to enhance performance and understand mechanisms of injury [1], [2], [3], [4], [5]. In robotics research, similar efforts improve the dynamic performance of multi-degree-of freedom manipulators without compromising safety [6]. In both areas, optimal performance of a dynamic skill (or a task) is affected by kinematic constraints and torque generating capacities.

Multi-body dynamics can help determine whether an athlete is moving optimally by estimating muscle movement to calculate effort. Inspired by human behaviors, our early work in robot control encoded tasks and diverse constraints into artificial potential fields captured human-like goal-driven behaviors [7]. This concept was later formalized in the task oriented operational space dynamic framework [8], [9]. Earlier work aimed to characterize some element of human motion [10], [11], [12] [14], [13], [15], [16], [17]. More recently, our efforts have concentrated on the synthesis and analysis of human motion using efficient techniques in robotics research [18], [19].

In this paper we present a robotics method for the characterization of human skills involving task-driven dynamic motion, and implement it for the analysis of elite athletic skills. The formulation of the dynamic characterization of manipulator systems including the operational space acceleration characteristics reflected at their end-effector are reviewed, the application of this performance characterization to the human motion analysis is described, and the acceleration characteristics of an elite athletic skill using a full-body musculoskeletal model are presented.

## II. METHODS

### A. Experiments

Motion analysis data were collected for an elite college-level golfer performing a full swing using a 9 iron club. Three-dimensional retro-reflective marker trajectories were recorded at 120Hz using an 8-camera motion capture system (Vicon, OMG plc, Oxford UK). A static trial was performed on the subject to assist scaling the musculoskeletal model (with markers attached to the medial and lateral femoral epicondyles and medial and lateral malleoli). Three-marker clusters were placed on the subject's feet, thigh, and shank for tracking purposes [20]. Four markers were placed on both the pelvis (anterior and posterior superior iliac spines) and torso (acromion processes, seventh cervical spine, and sternal notch). The ground reaction forces and moments were measured at 600Hz from a force-plate (Bertec Corporation, Columbus, OH). Marker trajectories were low-pass filtered using a zero-lag fourth-order Butterworth filter with a cut-off frequency of 15Hz. The athlete was notified about the nature of the study and signed informed consent consistent with the policies of the Institutional Review Board of Stanford University.

### B. Dynamic Simulations

We used the collected marker trajectories to generate a subject-specific simulation in OpenSim [21]. A 120 segment, 177 degree-of-freedom (dof) musculoskeletal model was used to create the dynamic simulation (Fig. 1). The hip was modeled as a ball-and-socket joint (3 dofs), the knee was modeled as a custom joint with 1 dof [22], and the foot and ankle were modeled as a custom joint with 2 dofs (dorsiflexion and plantar flexion at the ankle joint; eversion

*This work was supported by the Simbios National Center for Biomedical Computing Grant (http://simbios.stanford.edu/, NIH GM072970) and the Honda Company

[1]E. Demircan and O. Khatib are with the Artificial Intelligence Laboratory, Computer Science, Stanford University, 94305 California, USA emeld at stanford.edu, okhatib at cs.stanford.edu

[2]T. F. Besier is with the Auckland Bioengineering Institute, University of Auckland, New Zealand t.besier at auckland.ac.nz

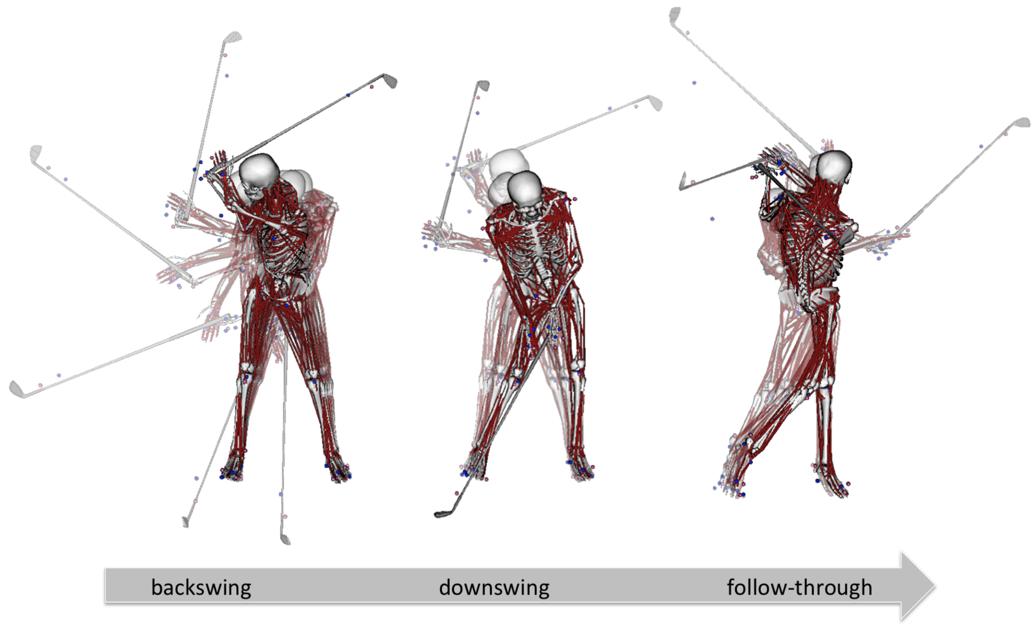


Fig. 1. Full swing simulation of a golf swing using the OpenSim musculoskeletal model

and inversion at the tarsal joint). Lumbar motion was modeled as a ball-and-socket joint (3 dofs) [23]. The shoulder was modeled as a ball-and-socket joint (3 dofs) [24] with additional 6 dofs representing the movement of scapula and clavicle, the elbow was modeled with a revolute joint (1 dof) and the wrist was modeled with a custom joint with 3 dofs (flexion and extension, ulnar and radial deviations, pronation and supination). The upper extremity, lower extremity and back joints were actuated by 323 musculotendon actuators [25], [23]

The full body model was scaled to match subject's anthropometry based on experimentally measured markers placed on anatomical landmarks. A virtual marker set was placed on the model based on these anatomical landmarks. A golf club (9 iron) was added to the simulation and its inertia was calculated using [26] in order to track the marker attached on the club. An inverse kinematics algorithm solved for the joint angles that minimized the difference between the experimentally measured marker positions and the virtual markers on the model. Fig. 1 illustrates the simulations generated for the full golf swing.

### C. Operational Space Formulation

In robotics research, the *Operational Space Formulation* [9] was introduced to address the dynamic interaction between a robot's task-space motion and force. To characterize the additional task redundancy, the operational space formulation defines a dynamically consistent task null space. Multiple operational tasks can be controlled if they are combined into a single task vector and additional criteria can be controlled within the task-consistent null-space. A task can be defined to be any formal description of desired activity that can be explicitly represented as a function of the joint coordinates, $q$ , $\dot{q}$ and $\ddot{q}$. Multiple tasks can be combined into a single task definition in a higher dimensional space, as long as they are kinematically consistent with each other. The full task is represented as the $mx1$ vector, $x_t = x_t(q)$, formed by vertically concatenating the coordinates of the operational points. The Jacobian matrix associated with the task, $x_t$, is denoted by $J_t$. The joint space equations of motion can be expressed as,

$$A(q)\ddot{q} + b(q,\dot{q}) + g(q) + J_{ext}^T F_{ext} = \Gamma, \quad (1)$$

where $q$ is the vector of $n$ joint coordinates, $A(q)$ is the $nxn$ kinetic energy matrix, b($q$,$\dot{q}$) is the $nx1$ vector of centrifugal and Coriolis joint forces, $g(q)$ is the $nx1$ vector of gravity, and $\Gamma$ is the $nx1$ vector of generalized joint forces (torques). In the presence of external forces in the system, the associated Jacobian and reaction force vector are $J_{ext}$ and $F_{ext}$, respectively. To simplify notation, we will often refrain from explicitly denoting the functional dependence of these quantities on q and $\dot{q}$.

The task dynamic behavior can be obtained by projecting the system dynamics (1) into the space associated with the task, using the generalized inverse of the Jacobian, $J_t$. This generalized inverse of the Jacobian has been showed to be unique and dynamically consistent [9], [27] and given by,

$$\bar{J} = A^{-1}J_t^T(J_t A^{-1} J_t^T)^{-1}, \quad (2)$$

The dynamic behavior associated with the task, $x_t$ can be obtained by,

$$\bar{J}_t^T(A\ddot{q}+b+g+\Gamma_{ext} = \Gamma) \Rightarrow \Lambda_t\ddot{x}_t+\mu_t+p_t+R_t = F_t. \quad (3)$$

In the operational space, $\Lambda_t$ is the $mxm$ kinetic energy matrix associated with the task, and $\mu_t$, $p_t$, $R_t$ and $F_t$ are, respectively, the centrifugal and Coriolis force vector, gravity vector, reaction force vector and generalized force acting along the direction of the task, $x_t$. This process provides a description of the dynamics in task coordinates rather than joint space coordinates (while joint space coordinates are still present in (3), the inertial term involves task space accelerations rather than joint space accelerations). The control framework defined in terms of the relevant task coordinates, $x_t$ can be represented using a relevant operational space force, $F_t$ acting along the same direction. The forces acting along given task coordinates can be mapped to a joint torque, $\Gamma_{task}$ by the relationship,

$$\Gamma_{task} = J_t^T F_t. \tag{4}$$

### D. Analysis of Acceleration Characteristics

In robotics research, visualization tools enable the evaluation of various performance criteria, such as effective mass, acceleration limits, velocity limits, etc. The tools render scaled ellipsoid or convex hulls at a specific point of robot body at a specific posture. Such renderings are results of observations at the point and the posture. These visualized results are being used to assist designing robot kinematics or deciding components by providing senses of performance for the situations when the robot executing assigned tasks with assigned end-effectors.

We begin the robotics-based analysis of human motion by introducing the characterization of operational space accelerations for a given task. The analysis of the operational space accelerations is motivated by the successful extension of operational space control to analyze the dynamic performance of robotic systems [28]. In this framework, the idea is to map the analysis of bounds on joint torques to the available end-effector accelerations in the workspace of the manipulator. An acceleration limit in a direction is a linear combination of cases where every actuator is saturated in one of both directions. Thus, if we find every acceleration limit of $2^N$ cases, where $N$ represents the degree of freedom of a robot, we can find the complete geometry of acceleration limit in every direction. But for a large $N$, it is not feasible to compute all limits of $2^N$ cases in reasonable time, thus we sample $M$ limits which is big enough to show the trend and small enough to be feasible.

This model can be applied to characterize the acceleration bounds in human dynamic skills shaped by the skeletal mechanics and physiological parameters. For a human musculoskeletal system of n degrees of freedom and r muscles, a set of muscle forces, $m$, arises based on muscle activations, as well as the skeletal configuration, $q$ and $\dot{q}$. These muscle forces are related to the joint torques, $\Gamma$, through the $rxn$ muscle Jacobian matrix, $L(q)$:

$$\Gamma = L(q)^T m, \tag{5}$$

where $m$ is the vector of net muscle forces (active and passive components, with an appropriate sign convention adopted) and the muscle Jacobian, $L(q)$ relates the skeletal configuration, $q$, to the musculo-tendon lenghts, $l$, through the relation $dl = L(q)dq$ . The musculoskeletal dynamics are driven by the joint torques given in (5), resulting in motion of the system.

In (5), $\Gamma$ is the $nx1$ vector of muscle induced joint torques and includes the torques required to compensate for gravity and torques required to produce the desired motion. So, the muscle induced joint torque/operational space acceleration relationship can be given as,

$$\ddot{x} = J(q)A(q)^{-1}(\Gamma - J_{c_1}^T F_{ext_1} - J_{c_2}^T F_{ext_2}). \tag{6}$$

where $J(q)$ and $A(q)$ are respectively the Jacobian matrix and joint space kinetic energy matrix. $F_{ext_1}$ and $F_{ext_2}$ capture the external forces/moments in the system at two different contact points $c_1$ and $c_2$. $J_{c_1}^T$ and $J_{c_2}^T$ are the corresponding Jacobian matrices at each contact point where the external forces are applied. In this model, the available operational space accelerations are characterized by the isotropic accelerations, defined as the maximum acceleration achievable in or about every direction in task space. The feasible range of operational space accelerations can be determined using (6) given the bounds on the muscle induced joint torque capacities by,

$$0 < \Gamma < L(q)^T m_{max}. \tag{7}$$

where $m_{max}$ is the vector of muscle force generating capacities.

To graphically illustrate this methodology, bounds on the feasible set of acceleration can be calculated by the convex hull of the affine transformation of a hypercube for $r$ muscles. The hypercube describing the set of allowable muscle induced torques has $2^r$ vertices.

To evaluate the transfer of muscle forces to the operational space accelerations we grouped the muscles according to their primary function (Table I). These groups were determined based on the most active muscles during the golf swing [29] and the muscles that contributed most to the resulting acceleration of the club head.

The torque generating capacities of 100 muscles (left and right upper body, left and right lower body and back muscles) spanning the right/left shoulder joints and the right/left hip joints were mapped into the operational space accelerations of the club head during the full swing. The bounds on the feasible set of acceleration were calculated by the convex hull of the affine transformation of a hypercube for the 100 muscles. The hypercube describing the set of allowable muscle induced torques has $2^{100}$ vertices.

## III. RESULTS

The available set of the golf club head accelerations in task space are illustrated for four different golf club head configurations in Fig. 2. Each 3-D parallelepiped represents the feasible set of operational space accelerations for a different club configuration during terminal downswing. During this phase, the acceleration boundaries are almost in line with the trajectory of the club head at the final few frames prior to ball contact. This analysis reveals that the subject tries to follow

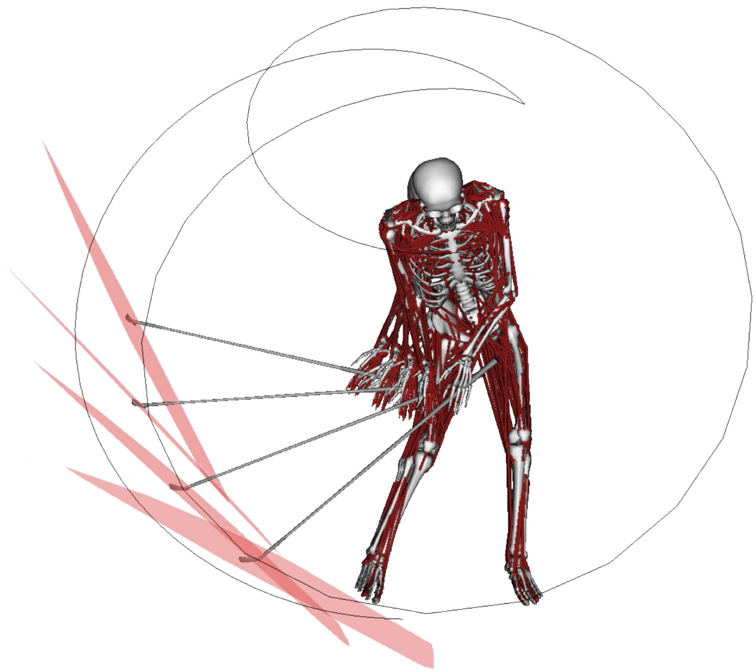

Fig. 2. The acceleration boundaries of the golf club of an elite college-level golfer. The 3-D parallelepipeds represent the feasible sets of operational space accelerations for 4 different club configurations during the acceleration phase of the swing.

TABLE I
FUNCTIONAL GROUPS OF MUSCLES USED IN THE GOLF SWING ANALYSIS

| Shoulder Adduction | Shoulder Abduction |
|---|---|
| Coracobranchialis | Deltoid |
| Infraspinatus | Subscapularis |
| Lattissimus dorsi | Trapezius |
| Pectoralis major | |
| Teres major | |
| **Scapular Retraction** | **Scapular Elevation/Depression** |
| Trapezius | Levator scapulae |
| | Lattisimus dorsi |
| | Trapezius |
| **Arm Flexion** | **Arm Extension** |
| Biceps branchii | Lattissimus dorsi |
| Coracobranchialis | Teres major |
| Pectoralis major | Triceps branchii |
| **Hip Adduction** | **Hip Abduction** |
| Adductor magnus | Gluteus medius |
| **Hip Flexion** | **Hip Extension** |
| Gluteus medius | Adductor magnus |
| | Biceps femoris |
| | Gluteus maximus |
| | Semimembranosus |
| **Knee Flexion** | **Knee Extension** |
| Biceps femoris | Vastus lateralis |
| Semimembranosus | |
| **Trunk Rotation** | |
| External oblique | |
| Internal oblique | |

the maximum available operational space acceleration, the path that may optimize the swing by maximizing the club head accelerations.

Fig. 3 shows the feasible set of available operational accelerations in the coronal plane (ie. plane of the swing) prior to ball contact. Here, the experimentally measured club head acceleration is shown with a blue arrow within the set (red hypercube). The graph in Fig. 3 shows that the acceleration needed to generate the motion of the golf club is directed toward the maximum operational space acceleration available at that configuration taking into account the gravity effect and the external forces (ie. ground reaction forces) in the system.

## IV. CONCLUSIONS

Driven by the hypothesis that elite performers select the most efficient transmission from muscle induced torque capacity to the resulting task, the aim of this study was to present a robotics approach to analyze elite golfer skills in the context of the desired task and the physiological constraints. Three-dimensional muscle-actuated dynamic simulation of a full swing was created, the characteristics of the relationship governing the transmission of muscle forces to the operational space accelerations of golf clubs were used to evaluate the dynamic performance in golfing skill. Analysis indicated that during the late downswing phase, the elite golfer transfers his muscular effort in a way to maximize the golf club acceleration in operational space. This confirms our hypothesis that the athlete uses most of the available muscle torque capacity while achieving the actual linear acceleration of the golf club head.

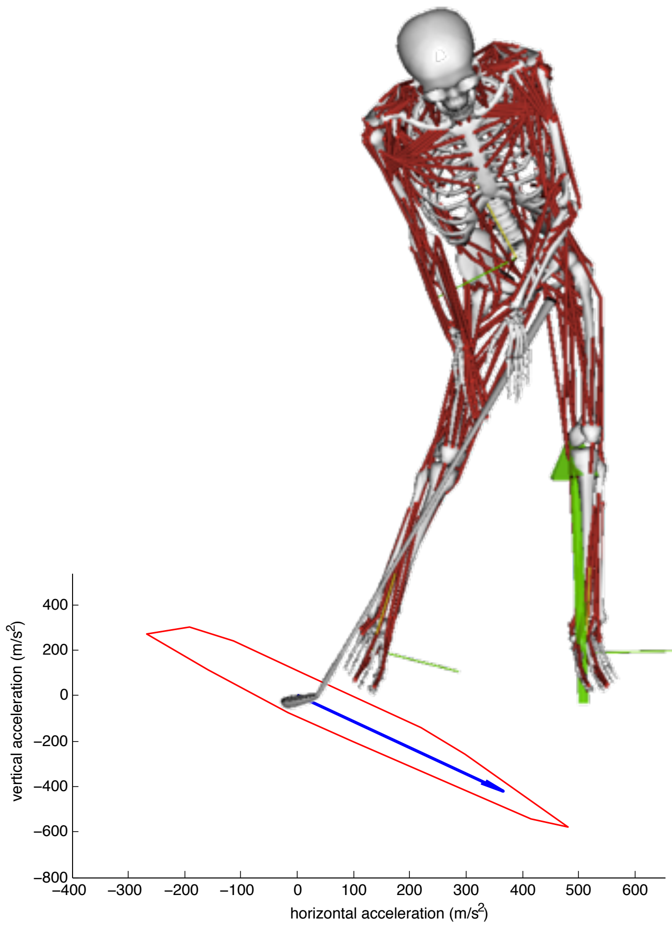


Fig. 3. Experimentally measured club head linear acceleration (blue arrow) in coronal plane within the available operational space accelerations (red hypercube) including the gravity effect and the reaction forces (green arrow) prior to ball contact.

In our approach, the dynamic performance that suits the golfer can be defined as the ability to achieve maximal golf club velocity before impact given the physiological constraints of the system (i.e. limb length, joint range of motion, and muscle strength and contraction velocity). The physiological constraints that affect human motion include the joint constraints (the range of motion at a joint), the segment constraints (the lengths of each segment) and the muscle constraints including physiological cross-section of a muscle, maximum contraction velocity, moment arm and line of action.

The results of this study show that humans follow a path of trajectory in line with the maximum available operational space accelerations benefiting from their physiology. They confirm our previous analysis of an elite football throwing motion [18] and support our hypothesis that elite players maximize the transmission of muscle strength to perform a dynamic task. This observation was previously supported by the robotics-based characterization of the operational space accelerations in athletic throwing performance (Fig. 4). Here, we extended our approach to account for the effects of contact with the environment.

Understanding how muscle capacities coupled with the body posture transfer to task-space accelerations may help to clarify the strategy to optimize a dynamic motion in the context of desired task and physiological constraints, which is applicable for both robot control and human performance evaluation. Driven by the motivation to understand human skills, the task-based approach introduced in this paper provides a basis for the optimization of dynamic performance in the presence of the task, posture, contact with the environment and physiological constraints.

The three dimensional muscle-actuated dynamic simulation created in this study can help to generalize the physio-mechanical criteria associated with any human postural or dynamic skill in presence of contacts and constraints and this information may be used for efficient robot control. This robotics-based characterization of human motion may be used together with whole-body operational space controllers to synthesize subject-specific optimal performance and to predict motion patterns that might lead to injury. The motion analysis may support important clinical analyzes used in many fields including the reeducation of patients, physical therapy and human performance augmentation.

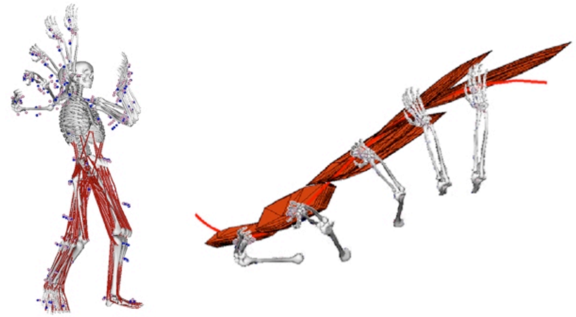

Fig. 4. Operational space acceleration characteristics of an elite football throwing [18].

## V. ACKNOWLEDGMENTS

The authors thank Ayman Habib and Ajay Seth for their comments and help for this study. This work was supported by the Simbios National Center for Biomedical Computing Grant NIH GM072970 and the Honda Company.

## REFERENCES

[1] D. Fortenbaugh and G.S. Fleisig and J.R. Andrews, "Baseball Pitching Biomechanics in Relation to Injury Risk and Performance", *Sports Health: A Multidisciplinary Approach*, vol. 1, 2009, pp 314-320.

[2] G.S. Fleisig and S.W. Barrentine and R.F. Escamilla and J.R. Andrews, "Biomechanics of Overhand Throwing with Implications for Injuries" *Sports Medicine*, vol. 21(6), 1996, pp 421-437.

[3] T.F. Besier and D.G. Loyd and T.R. Ackland and J.L Cochrane, "Anticipatory Effects on Knee Joint Loading During Running and Cutting Maneuvers" *Medicine and Science in Sports and Exercise*, vol. 22(7), 2001, pp 1176-1181.

[4] J.R. Steele, "Factors Affecting Performance in Netball - Implications for Improving Performance and Injury Reduction" *Sports Medicine*, vol. 10(2), 2001, pp 88-102.

[5] A.M. Chaudhari and B.K. Hearn and T.P. Andriacchi, "Sport-dependent Variations in Arm Position During Single-Limb Landing Influence Knee Loading - Implications for Anterior Cruciate Ligament Injury" *Am J Sports Med*, vol. 33(6), 2005, pp 824-830.

[6] M. Zinn and O. Khatib and B. Roth and J. K. Salisbury, "A New Actuation Approach for Human Friendly Robot Design", *The International Journal of Robotics Research*, vol. 23, 2004, pp 379-398.

[7] O. Khatib and J.F. Le Maitre, "Dynamic Control of Manipulators Operating in a Complex Environment" *in Proceedings of RoManSy78*, Udine, Italy, 1978, pp. 267-282.

[8] O. Khatib, "Real-time Obstacle Avoidance for Manipulators and Mobile Robots" *The International Journal of Robotics Research*, vol. 5(1), 1986, pp 90-98.

[9] O. Khatib, "A Unified Approach for Motion and Force Control of Robot Manipulators: The Operational Space Formulation" *International Journal of Robotics and Automation*, vol. 3(1), 1987, pp 43-53.

[10] Y. Nakamura and K. Yamane and I. Suzuki and Y. Fujita, "Dynamic computation of musculo-skeletal human model based on efficient algorithm for closed kinematic chains" *in Proceedings of the 2nd International Symposium on Adaptive Motion of Animals and Machines*, Kyoto, Japan, 2003.

[11] F. Hermens and S. Gielen, "Posture-based or trajectory-based movement planning: a comparison of direct and indirect pointing movements" *Experimental Brain Research*, vol. 159(3), 2004, pp 304-348.

[12] P. Vetter and T. Flash and D.M. Wolpert, "Planning movements in a simple redundant task" *Current Biology*, vol. 12(6), 2002, pp 488-491.

[13] F. Lacquaniti and J.F. Soechting, "Coordination of arm and wrist motion during a reaching task" *Journal of Neuroscience*, vol. 2(4), 1982, pp 399-408.

[14] V. DeSapio and J. Warren and O. Khatib, "Predicting reaching postures using a kinematically constrained shoulder model" *in Proceedings of the Tenth International Symposium Advances in Robot Kinematics*, Heidelberg, Germany, 2006, pp. 209-218.

[15] T. Kang and J. He and S.I. Helms Tillery, "Determining natural arm configuration along a reaching trajectory" *Experimental Brain Research*, vol. 167(3), 2005, pp 352-361.

[16] J.F. Soechting and C.A. Buneo and U. Herrmann and M. Flanders, "Moving Effortlessly in Three Dimensions: Does Donders Law Apply to Arm Movement?" *Journal of Neuroscience*, vol. 15, 1995, pp 6271-6280.

[17] Y. Uno and M. Kawato and R. Suzuki, "Formation and control of optimal trajectory in human multijoint arm movement" *Biological Cybernetics*, vol. 61, 1989, pp 89-101.

[18] O. Khatib and E. Demircan and V. DeSapio and L. Sentis and T. Besier and S. Delp, "Robotics-based Synthesis of Human Motion" *Journal of Physiology - Paris*, vol. 103, 2009, pp 211-219.

[19] E. Demircan and L. Sentis and V. De Sapio and O. Khatib, "Human Motion Reconstruction by Direct Control of Marker Trajectories" *in Proceedings of the Eleventh International Symposium Advances in Robot Kinematics*, Batz-sur-Mer, France, 2008, pp. 263–272.

[20] T.F. Besier and D.L. Sturnieks and J.A. Alderson and D.G. Lloyd, "Repeatability of Gait Data Using a Functional Hip Joint Centre and a Mean Helical Knee Axis" *J. Biomech*, vol. 36, 2003, pp 1159-1168.

[21] S.L. Delp and F.C. Anderson and A.S. Arnold and P. Loan and A. Habib and C.T. John and E. Guendelman and D.G. Thelen, "OpenSim: Open-source Software to Create and Analyze Dynamic Simulations of Movement" *IEEE Transactions on Biomedical Engineering*, vol. 55, 2007, pp 1940-1950.

[22] A. Seth and M. Sherman and P. Eastman and S.L. Delp, "Minimal formulation of joint motion for biomechanisms" *Nonlinear Dynamics*, 2010.

[23] F.C. Anderson and M.G. Pandy, "A dynamic optimization solution for vertical jumping in threed imensions" *Comput.Meth.Biomech.Biomed.Eng*, vol. 2(3), 2007, pp 201-231.

[24] K.R. Holzbaur and W.M. Murray and S.L. Delp, "A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control" *Experimental Brain Research*, vol. 33(6), 2005, pp 829-840.

[25] S.L. Delp and P. Loan and M.G. Hoy and F.E. Zajac and E.L. Topp and J.M. Rosen, "An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures" *IEEE Transactions on Biomedical Engineering*, vol. 37(8), 1990, pp 757-767.

[26] M.I. Friswell and M.G. Smart and J.E. Mottershead, "Updating Finite Element Models of Golf Clubs" *in Proceedings of the International Modal Analysis Conference IMAC*, vol. 1, 1997, pp. 155-161.

[27] O. Khatib, "Inertial Properties in Robotics Manipulation: An Object-Level Framework" *The International Journal of Robotics Research*, vol. 14(1), 1995, pp 19-36.

[28] O. Khatib and J. Burdick, "Optimization of Dynamics in Manipulator Design: The Operational Space Formulation" *The International Journal of Robotics and Automation*, vol. 2(2), 1987, pp 90-98.

[29] A. McHardy and H. Pollard, "Muscle activity during the golf swing" *Br J Sports Med*, vol. 39, 2005, pp 799-804.