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ON MODEL VALIDATION USING THE REACHABLE 3D SPACE

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INTRODUCTION

Musculoskeletal models have been applied within multiple scientific areas such as ergonomics, sports science and orthopedics. With an increased maturation of the simulation technology, its application within clinical decision making and design of clinical products are emerging. This transition calls for patient-specific models that have undergone thorough validation prior to their application to avoid potentially harmful decisions to be made or poorly performing products.

The scope of this paper is to develop a new approach to model validation using 3D point clouds that are constructed as the reachable space for a given load case.

METHODS

One male subject (age: 24 years, mass: 76 kg, height: 1.75 m) participated in this study.

3D coordinates of retro-reflective markers attached to the pelvis, trunk, shoulder and arm were measured at 100 Hz using an eight-camera Qualisys system with QTM v.2.9. software (Qualisys, Gothenburg, Sweden). Within a specific time period of 60 seconds, his reachable space was explored under five different conditions: with no load and while carrying a dumbbell of 0.5, 1.0, 1.5 and 2.0 in his hand. All cases were repeated twice, which produces a point cloud of 12,000 per trial/payload. Only points generated anteriorly of the frontal plane were included for further analysis. A reference trial with the subject standing in a neutral position was also recorded.

An upper limb musculoskeletal model of the subject was built using the AnyBody Modeling System (AMS) v. 6.0.4. (AnyBody Technology A/S, Aalborg, Denmark). The model was based on the '*Standing Model*' from the AnyBody Managed Model Repository (AMMR) v.1.6.3. The trunk and pelvis were modelled as one rigid segment and the pelvis segment was grounded. The shoulder was modelled with 10-degrees-of-freedom (dof): sternoclavicular (3-dof);

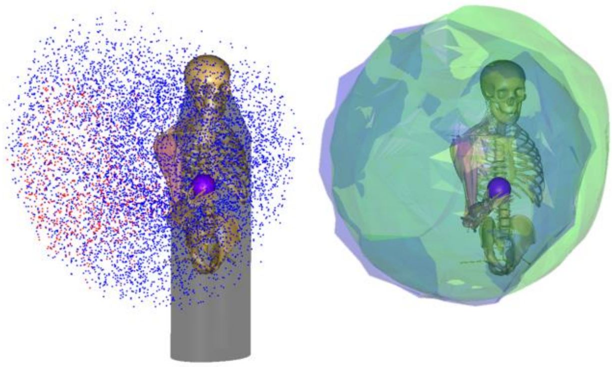

Fig 1: (***Left***) The pre-processed blue reachable space (MMACT ≤ 1) and red (MMACT > 1) point clouds for the unloaded case (0 kg); (***Right***) the respective post-processed polyhedral shapes of S (blue) with the overlapping R (green) spaces.

glenohumeral (3-dof); elbow (2-dof); and wrist (2-dof) joints. Inverse dynamic analysis was performed to compute the muscle activations using a cubic muscle recruitment criterion (no upper limit was considered) [1].

The reachable space was defined within an anatomical pelvis reference frame based on four anatomical landmarks (left and right anterior and posterior superior iliac spine) following the ISB recommendations.

To scale the segment lengths of the cadaver-based model to the subject, the optimization-based method of Andersen et al. [2] was applied together with a length-mass-fat scaling law to minimize the least-square difference between modelled and experimental marker trajectories during the reference trial. This scaling law takes as inputs the segment lengths, the subject's mass and height, and estimates the corresponding muscle mass per segment from which the muscle strengths are estimated.

To assess the reachable space of the model (Fig 1), 10,000 samples were generated by sampling the joint space using the Latin Hypercube Sampling method. The joints space was explored from the anatomical joint ranges-of-motion published by Chaffin [3]. For a given posture, i.e. a set of joint angles, an inverse dynamic analysis was executed and coordinates of

Table 1. Overlaping measures between real (R) and simulated (S) reachable spaces.

Space	R	S	R∩S	R	S	R∩S	R	S	R∩S	R	S	R∩S	R	S	R∩S
Weight (kg)		0.0			0.5			1.0			1.5			2.0	
Volume (m^3)	0.388	0.421	0.305	0.332	0.417	0.270	0.369	0.425	0.292	0.329	0.414	0.286	0.264	0.411	0.218
Overlap Coefficient	0.786	0.725	-	0.815	0.649	-	0.791	0.688	-	0.816	0.648	-	0.824	0.529	-
Dice Coefficient		0.754			0.722			0.736			0.722			0.644	
Hausdorff distance (m)		0.202			0.229			0.182			0.202			0.208	

a point located at the palm of the hand of the model was saved for further analysis. A point in the Cartesian space was "reachable" if the maximum muscle activity (MMACT) [1] was less than one, i.e. that the required force of all muscles were lower than their strength. If MMACT was larger than one, the point was "not reachable" (designated as red points in the cloud in Fig 1). As the volume of interest is the one containing points anterior to the frontal plane, a post-processing MATLAB routine (MathWorks, Massachusets, USA) removed undesirable points from the blue point cloud (MMACT ≤ 1).

Thus, all points posterior to a frontal plane, defined through the hip joint centers and right shoulder joint center, were removed. Sampling directly from the joint space can lead to postures, where the arm penetrates the skull or thorax, so these were also removed; points laying within the polyhedral shape (convex hull) defined by the trunk and skull of two cylinders centered at each half of the ribcage and an ellipsoid matching the skull, were removed using *inpolyhedron* in MATLAB (black region in Fig 1). Any posture where the arm and/or the forearm penetrate the trunk and skull convex hull shape was also not allowed and removed.

The concept of α-shapes is often used in computational geometry to get the "concave" shape of a point cloud [4]. The α-complex derives from the tetrahedral tessellation of points (Delaunay triangulation) acted by a carving sphere of radius α. The α-shape is its resultant boundary shape. If $\alpha = \infty$ the convex hull and if $\alpha = 0$, it is the singular point cloud. An $\alpha = 0.2$ m was chosen upon visual inspection using MATLAB *alphaShape* function.

To compare the real, R, and simulated, S, reachable spaces, multiple metrics were employed. The selected measures, as described in [5], were implemented in MATLAB: volume V (*volume* function); overlap coefficient, V(R∩S)/V(R) and V(R∩S)/V(S); Dice similarity coefficient, V(R∩S)/(V(R)/2+V(S)/2); Hausdorff distance, which measures the maximum distance from any point in one cloud to the closest point in the other.

RESULTS AND DISCUSSION

The real (R) and simulated (S) reachable spaces are represented together in Fig 1 and the selected metrics presented in Table 1. These preliminary results suggest that the current musculoskeletal model is stronger than the subject. The evidence is the volume S, which remains almost constant as the payload increases while R clearly shrinks. Moreover, both overlap coefficient increase and Dice coefficient decrease support that R is converging to a subset of S, i.e. R ⊂ S. Finally, the Hausdorff distance is slightly high. This can be explained from a visible void in S on the left lateral side of the body, which is covered by R (Fig 1). It indicates that the literature values [3] for the ranges-of-motion may not fully represent the capabilities of the subject. A potential solution is to assess the subject's passive range-of-motion and use this as input.

The length-mass-fat scaling law seems not to fully capture the strength characteristic of the subject. This might be improved by performing isometric and isokinetic strength measurements of the subject to which the model can be calibrated. This is part of future work.

CONCLUSIONS

In this paper, we presented a general method for validation of the strength scaling of musculoskeletal models based on the so-called reachable space. It demonstrated the preliminary validation of the length-mass-fat scaling law to scale to a specific subject. The results showed that the model in general is stronger than the test subject and that more advanced scaling methods are likely required to more accurately represent the subject.

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