Generation of Percentile Values for Human Joint Torque Characteristics

Florian Engstler and Heiner Bubb

Institute of Ergonomics, Technische Universität München,
Boltzmannstr. 15, 85747 Garching, Germany
engstler@lfe.mw.tum.de, bubb@lfe.mw.tum.de

Abstract. This pilot study presents an approach to generate percentile values for joint torque characteristics of digital human models. Detailed angle specific joint torque measurements of few subjects are set in relation to extensive measurements of external maximum forces including percentile values based on many subjects by using muti-body simulation. Results indicate the applicability of the approach but do not generate results of high validity due to some sources of errors along the process. More experiments solving these issues and generating valid results are being planned.

Keywords: DHM, joint force, percentile.

1 Introduction

Today's digital human models (DHM) offer an increasingly comprehensive simulation of human characteristics. One aspect currently being addressed by numerous research groups around the world is the integration of human forces allowing for force-based posture- and motion-simulation.

Bubb and Fritzsche [1] give an overview of current developments in digital human modeling presenting the different approaches ranging from simply integrating force data for specific tasks at defined postures to detailed simulation of individual muscles in musculoskeletal models like the AnyBody modeling system [2]. We concentrate on an approach at joint level: With the knowledge of internal joint torques it is possible to simulate external forces, postures and motions without the need of having a detailed understanding of the underlying muscle activities (see Seitz [3] and Fritzsche [4]).

Generally, the force data used for human modeling is obtained experimentally: Subjects exert maximum forces for single joint degrees of freedom (DOF), which are then converted to joint torque. With joint torque depending on joint angle and force direction, numerous measurements under different postures are necessary making the process extremely time-consuming. For this reason available studies on maximum joint torque are unfortunately based on a very small number of subjects. Nonetheless such data has been integrated e.g. into the DHM Ramsis driving the integrated force-based posture calculation and the prediction of external forces [3]. As the limited amount of data does not suffice for the application of sound statistical analysis, the dependency e.g. of gender and age are currently calculated on the basis of factors coming from literature [5] or by so-called synthetic distributions [6]. However, there

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is no direct connection between the force-capabilities of the DHM and the actual force distribution in the population like we know it from body dimensions for instance. In short: it remains unclear, how strong the DHM actually is. This shows the necessity for percentile values of human joint torque information. Because of the high effort it is hardly realizable to measure this data on a statistically sufficient number of subjects.

On the other hand there are experimental studies on maximum forces with high numbers of subjects. These studies typically measured external forces for certain mostly industry-related tasks like lifting loads, pushing crates, etc. allowing for the calculation of force percentile values. They are, however, missing information on posture and internal joint torque.

This paper presents a possible approach to link these two types of experiments allowing for a relation of percentile values to joint torque data.

2 Human Maximum Force Measurements

This section gives a short overview on definitions of maximum force used in the scientific community and puts this work into the context.

2.1 Definitions and Measurement Protocols of Maximum Force

There are different definitions and measurement protocols for maximum force capabilities of human beings. Force exertion can be static or dynamic and the assessment can be isometric, isokinetic, isoinertial or psychophysical [7, 8]. The vast majority of data in the literature are isometric static forces and our approach relates to this method as well.

There are different methods how to measure isometric force concerning the type of force exertion. Kroemer [9] distinguishes between the “plateau-”, “ramp-” and “impulse-method”. When using the plateau-method a constant maximum force has to be applied for about 3 to 5 seconds. One evident problem is that subjects normally won’t apply their maximum possible force if they aren’t used to the experiments. A kind of safety thinking leads them to conservatively distribute their force over the 5 seconds as they don’t know how long they are able to maintain a certain force level. Therefore subjects need to be trained to use this method. With the ramp-method the subject continuously increases the applied force until exhaustion. With this method an authentic maximum force will be measured, however, this force is only applied for a split second and therefore the informative value of the result can be debatable. The impulse-method is not recommendable as the maximum force is supposed to be applied in an instance. As it’s not possible to mobilize maximum force within fractions of a second, the result is no real maximum value. The peak results mainly from the impetus of the motion rather than muscle force.

Preliminary tests of Rühmann and Schmidtke [5] argue for the ramp-method (reliability coefficient = 0.98). However, plateau- and ramp-method or slight variations of both are widely used in the literature.

2.2 Measuring External Maximum Force

Most of the experimental studies on maximum forces, especially in the past, have been driven by the need for task-related data for the design of specific workplaces, working environments or products. Therefore typical types of force exertion for industrial work or user-product interaction have been studied: lifting loads at different positions, pushing and pulling crates, operating handles, etc. Daams [10] gives an overview of such measurements. The common ground of these studies are the relatively undefined experimental restrictions for the subjects: Although measuring different anthropometries, the place of force application is mostly fixed in space leading to different postures for different anthropometries. Additionally, the subjects have the freedom to take the posture they like in order to fulfill the task (except for some regulations e.g. where to put their feet), but detailed information on the individual subject's postures are generally missing. However, this kind of experiments is normally done on a high number of subjects. Rühmann and Schmidtke [5] measured maximum external isometric forces for 1113 females and 1967 males for 14 different tasks using the ramp-method (see Fig. 1). Other studies offer comparable sample sizes giving the results high statistic significance (e.g. Glitsch et al. [11], Rohmert et al. [12]). The documented data is mostly demographic information related to force values: force percentiles for gender or age groups for instance. Unfortunately this kind of data can therefore not be directly adopted for the use in DHMs as no information on the subject-internal processes of force exertion is contained.

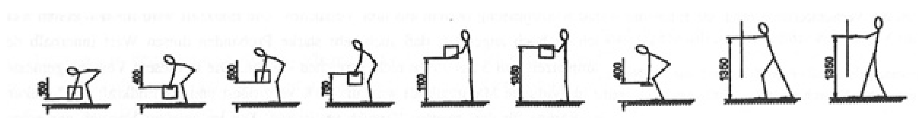

Fig. 1. Experiments on task specific external forces by Rühmann and Schmidtke [5]. Some lifting tasks were done with one and two hands.

2.3 Measuring Joint-Level Maximum Force

In order to simulate forces with DHMs force information at joint level is required. Some measurements for single joints or extremities can be found in the literature (e.g. [13], [14], [15] and [16]), but generally few studies obtained such data and on a very small number of subjects only. This is due to the high effort caused by joint-specific measurements: with joint torque being dependent on the joint angle a very high number of trials become necessary. This is especially true for complex tree-dimensional joints like the shoulder. In course of the EU FP5 project "Realman" (IST-2000-29357) [17] maximum joint torque had been measured for eight subjects in a period of three years. Subjects applied isometric forces for single joint DOFs which were measured with the plateau-method. The measurements covered most major joints: hip, knee, shoulder, elbow and wrist. The ankle and especially the spine had unfortunately not been measured.

3 Approach to Percentile Values at Joint-Level

Our approach tries to build a link between the detailed joint-level information of individual subjects and the percentile values of large measurements on external forces. The basic idea is to have subjects with known joint-torque properties perform experiments for external forces and relate their joint-torque utilization to percentile values obtained in such experiments. This paper describes the approach based on data from the Realman-project and a recreation of the experiments from Rühmann and Schmidtke. The concept is illustrated in Fig. 2 and will be described in detail below.

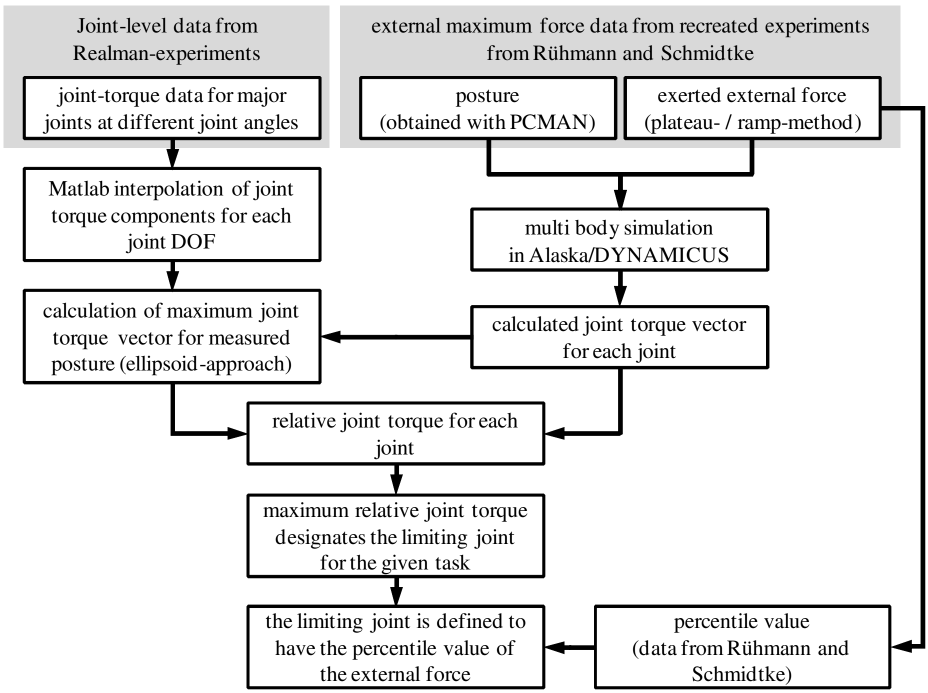

Fig. 2. Concept for generation of percentile values of human joint torque characteristics

3.1 Joint-Level Data

This pilot study is based on experiments with one male subject (28 years old, 1.74 m tall and 64.5 kg weight). He was the only subject still available from the Realman-project with a total of 936 single joint torque values measured which could be reused for this study. The data are tabulated torque values for different orthogonal directions of force exertion at a given joint angle combination. For each shoulder for instance six torque values (flexion, extension, abduction, adduction, internal and external rotation) have been measured for 59 different postures.

Firstly, the subject's torque data for specific joint angles has to be interpolated in order to calculate maximum joint torque values for any joint angle combinations. This is done by a multidimensional polynomial regression in Matlab showing the best results among the popular mathematical methods [4]. An exemplary formula (1) for elbow flexion (2 rotational DOF) can be seen below (α = elbow flexion angle; γ = forearm pronation angle).

$$T_{max} = 39.9 + 0.5\alpha - 2.7 \cdot 10^{-3}\alpha^2 + 0.2\gamma - 2.4 \cdot 10^{-3}\alpha\gamma - 1.2 \cdot 10^{-3}\gamma^2 \quad (1)$$

When exerting force in any direction different to the six directions measured, the maximum joint torque value has to be calculated. Schäfer [18] and Rothaug [19] described joint torque for a 3 rotational DOF joint at a given joint angle as an unsymmetrical ellipsoid defined by the six measured values with the ellipsoid surface defining the maximum joint torque possible (see Fig. 3). Any vector inside the ellipsoid would be sub-maximum joint torque, a vector touching the surface would be maximum joint torque and any vector penetrating the surface could not be exerted by the subject. For joints with 2 rotational DOF like the elbow the representation would be an ellipse.

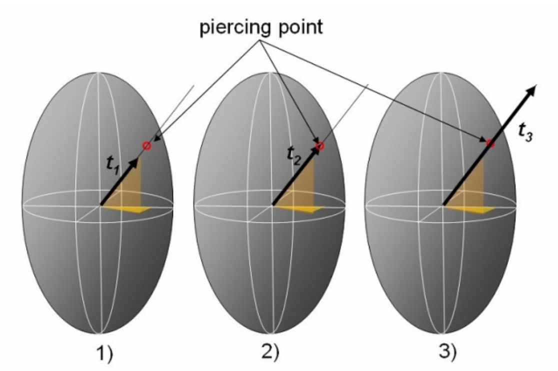

Fig. 3. Calculation of maximum joint torque based on an ellipsoid-approach (t_1 being sub maximal torque, t_2 being the maximal torque and t_3 exceeding the maximal torque) [3]

3.2 External Maximum Force

We recreated the measurement setup from the experiments done by Rühmann and Schmidtke and extended it by integrating the PCMAN posture measurement system [20]. This video-based software allows for marker-less measuring of the subject's anthropometry and posture and is compatible to the DHM Ramsis and the multi body modeling system Alaska/DYNAMICUS [21]. The subject performed 14 of the trials measured by Rühmann and Schmidtke. An exemplary trial can be seen in Fig. 4. According to the guidelines on force measurement from Kumar [22] one trial was repeated until the variance of the results was smaller than 10%. Additionally the subject was asked on his impression which joint might have been the limiting one for the trial.

As Rühmann and Schmidtke utilized different measurement protocols than the Realman-project, the subject performed every trial twice: once with the ramp-method and a second time with the plateau-method. Comparing the measurements showed the results of the ramp-method equal on average 1.25 times those of the plateau-method (standard deviation 0.15). The data obtained with the ramp-method are only used to

Fig. 4. Exemplary experiment according to Rühmann and Schmidtke with overlaid PCMAN measurement. The subject had to pull the handle upwards. Height of the handle and distance between right foot and handle had been specified.

assign the subject's external force to a percentile value coming from Rühmann and Schmidtke. The data from the plateau-method is, together with anthropometry and posture from PCMAN, transferred to the multi-body simulation.

3.3 Multi-body Simulation

Given the measured external force, anthropometry and posture the joint torque necessary for exerting the external force can be calculated for each joint using the multi-body modeling software Alaska/DYNAMICUS. The software offers an interface to RAMSIS and PCMAN giving the multi-body model the correct anthropometry and dynamic properties (joint segment weight, centre of gravity, etc.). Joint angles from PCMAN need to be transformed to the Alaska/DYNAMICUS joint coordinate system using Excel.

The simulation generates one joint torque vector for each joint of the model expressed in the Alaska/DYNAMICUS joint coordinate system. The vectors are then transformed back to PCMAN joint angles (see red arrows in Fig. 5). For the given orientation of the simulated joint torque vector the maximum joint torque vector can be calculated from the Realman measurements using the ellipsoid approach (yellow arrow). The absolute values of the vectors are then compared giving the relative joint torque for each joint.

3.4 Assignment of Percentile Values

The joint with the maximum relative load is designated to be the limiting joint for the given force exertion and is therefore responsible for the percentile value of the exerted external force. It is expected that the relative load of the limiting joint is near 100%. Some variance will however be inevitable due to inaccuracies during force- and posture-measurements. Obviously, percentile values can only be assigned to limiting joints.

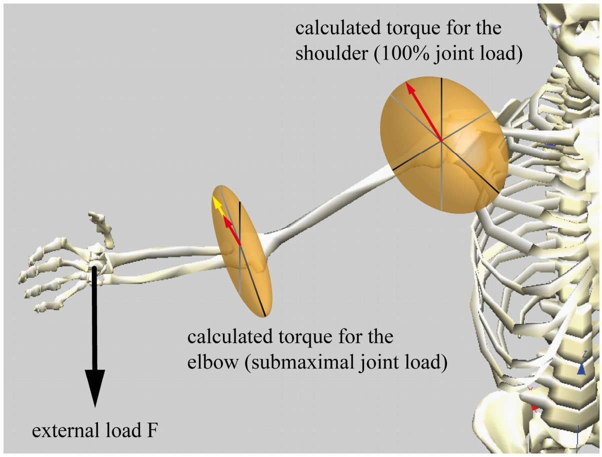

Fig. 5. Exemplary calculation of relative joint load based on an external force for elbow and shoulder

The percentile value of the external force can be directly related to the dimensions of the subject's maximum torque vector. To generate percentile distributions for joint torque additional steps are necessary: We assume the shape of the torque ellipsoid of the limiting joint to be representative for the whole population and thus being constant independently from its size. With this assumption the percentile value is related to the whole torque ellipsoid. The ellipsoid can now be scaled by calculating the torque distribution using mean and variance of the force measurements according to formulae 1-4 (index F indicating force measurements, index T indicating torque calculation). With

$$\frac{s_R}{\bar{x}_R} = \frac{s_T}{\bar{x}_T} \quad (1) \quad \text{and} \quad \frac{x_R - \bar{x}_R}{s_R} = \frac{x_T - \bar{x}_T}{s_T} \quad (2)$$

mean and variance of the joint torque can be calculated by

$$s_T = \frac{s_R \cdot x_T}{x_R} \quad (3) \quad \text{and} \quad \bar{x}_T = \frac{\bar{x}_R \cdot s_T}{s_R}\,. \quad (4)$$

4 Results

An exemplary result of relative joint torque values is depicted in Fig. 6. The subject had to pull one-handedly upwards while keeping a defined distance between foot and handle. His exerted force was 10.5th percentile. It can be seen that the knee joint exceeds 100% relative joint load. This can be easily explained: The posture measurement reported a slightly bent knee and thus Alaska/DYNAMICUS calculated a high joint torque for this posture. In reality however, the subject had fully stretched his knee not needing to exert noticeable joint torque. In other trials different joints, like the shoulder also exceeded 100% relative joint load. The explanation in this case is not that clear: The deviation from is assumed to be a combination of measurement inaccuracies from posture measurement, errors from maximum joint torque interpolation and the ellipsoid-approach and finally the possibility, that the subject did not actually exert his maximum strength during the experiments. The sensitivity to posture measurement errors was tested on the trial in Fig. 6 by slightly varying the joint angles for clavicle, shoulder and elbow by few degrees while still generating a plausible result in PCMAN. This generated a high difference for the relative load in the shoulder joint of +15% showing the necessity for a more accurate posture measurement. Furthermore, occasionally joint angles exceeded the range in which maximum joint torque had been measured during the Realman-project, so the calculated maximum joint torque was no longer an interpolation but an extrapolation of low validity. This occurred especially at hip and knee. Also, for some of the trials not depicted here it is expected and concordant to the subject's impression that the spine would be the limiting factor. As the spine had not been measured during the Realman-project the results do not actually identify the limiting joint. However, the resulting limiting joints generally correlate very well with the subject's statements.

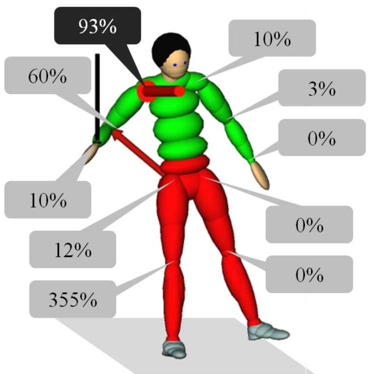

Fig. 6. Exemplary relative joint torque values of external load for a lifting task. The black vector indicates external load, red vectors indicate calculated joint torque for elbow and shoulder. The limiting joint is marked inverted.

5 Conclusion and Outlook

The presented approach was able to detect the limiting joints for given tasks of maximum force exertion. Due to inaccuracies along the process the results of relative joint torque and percentile values are however not of high validity. The need for further refinement especially of the experimental protocols became evident. Nonetheless, this pilot study showed the general applicability of our approach. To improve the validity of the results there are several issues to be dealt with in future work:

First of all the experiment needs to be repeated with a higher number of subjects. In course of the project "DHErgo" funded under the EU Seventh Framework Programme maximum joint torque will be measured similar to the Realman-project including all major joints with multiple young and elderly subjects. The measurement protocols and equipment are currently being improved and measuring equipments for additional joints like the spine and ankle are being developed. Furthermore, the subjects' posture will be recorded with a marker tracking system of high accuracy. For at least some of the subjects joint torque measurements are planned to be done at a higher level of detail which should allow for more accurate joint torque interpolation functions. In addition the ellipsoid approach will have to be put into question. It might well be good model for some joints, but is might not be suitable for all joints. Other mathematical descriptions will have to be tested. Furthermore, the ellipsoid shapes of different subjects will have to be combined in order to generate a mathematical description valid for the average population.

The subjects from DHErgo will also take part in experiments on external maximum force like those from Rühmann and Schmidtke described above. In addition we plan to recreate more experiments of this kind in order to have every joint as a limiting joint at least once. These experiments will be recorded with the marker tracking system as well.

All these actions should significantly improve the data quality allowing for a more promising application of the presented approach and more valid results.

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