A formula to predict patients’ gluteus medius muscle volume from hip joint geometry

Bernd Preininger a,*, Kathrin Schmorl a, Philipp von Roth a, Tobias Winkler a, Peter Schlattmann b, Georg Matziolis a, Carsten Perka a, Stephan Tohtza

a Department of Orthopaedics, Center for Musculoskeletal Surgery, Charité-Universitätsmedizin Berlin, Charitéplatz 1, D-10117 Berlin, Germany
b Department of Medical Statistics, Computer Sciences and Documentation, University Hospital of Friedrich-Schiller-University Jena, Jena, Germany

1. Introduction

The gluteus medius muscle (GM) plays a key role in exerting abduction force across the hip joint, providing stabilisation of the pelvis during single leg stance. Single leg stance allows the other leg to swing while the bodyweight is balanced on the contralateral leg and thereby is essential for human locomotion.

Insufficiency of the GM is clinically associated with a positive Trendelenburg sign and finally leads to a loss of pelvic control with an impaired ability to walk. The preservation of the GM during total hip arthroplasty (THA) is therefore regarded to be crucial for postoperative abduction force (Kumagai et al., 1997) and functional outcome. By limiting intraoperative muscle damage, postoperative complications such as limping or a positive Trendelenburg sign (Inan et al., 2005) can be minimised.

To limit muscle damage, minimally invasive approaches are increasingly used to implant hip endoprosthesis and the traditional transgluteal (Bauer et al., 1979) approach is applied more restrictively. Studies relating the functional outcomes after hip arthroplasty to the surgical approach showed a better early-postoperative hip joint function using muscle sparing approaches (Wohlrab et al., 2004; Murphy and Tannast, 2006; Muller et al., 2010; Preininger et al., 2010).

In order to restore best possible postoperative function not only intraoperative muscle preservation but also postoperative rehabilitation to regain muscle strength is essential. Rehabilitation programs are therefore an inherent component of the patient management after THA.

As yet there is no method of determining the goals for rehabilitation programs in terms of muscle tissue since it has not been possible to estimate reference values for individual muscle volumes so far. The muscle status of the contralateral side cannot serve as a very accurate template due to leg dominance and preoperative changes resulting from non-physiological loading and limp (Grimaldi et al., 2009).

Since muscle force correlates with muscle volume ($R^2 = 0.90$) (Tonson et al., 2008) the interrelations between the abduction force needed to stabilize the pelvis, hip joint geometry and body weight/
size imply a relationship between the individual volume of the abductor muscles, joint geometry and body weight/size (Carls et al., 2002; Charles et al., 2005; Lecerf et al., 2009) (Fig. 1).

The GM accounts for the largest part of the abduction force of the pelvirochanteric musculature surrounding the hip joint (Kumagai et al., 1997). We measured the hip joint geometry and the gluteus medius muscle volume (GMV) from 3D computed tomography (CT) scans in patients without manifest hip pathologies. Individual correlations between these parameters were analyzed. Due to differences in muscular physiology as well as in hip kinematics and muscle activity of the GM between males and females we included gender as a parameter in our investigations (Hicks et al., 2001; Russ and Kent-Braun, 2003; Chumanov et al., 2008; Wust et al., 2008).

The aim of this study was to find a way to predict the "physiological" volume of the GM in patients without hip joint diseases and thereby provide index values for the GMV. Such individual reference values could clinically be used to individually determine the goals for rehabilitation programs after THA.

2. Materials and methods

2.1. Demography

Pelvic CT-scan datasets of 102 patients (50 female) between 2003 and 2008 were randomly chosen from the database of the radiological department of the clinic. Demographic data collected included gender, age, height, weight (Table 1). Scans included the pelvis from the iliac crest and the proximal femur at least down to the lesser trochanter.

Exclusion criteria were osteoarthritis Kellgren–Lawrence score ≥ 2, hip dysplasia, present hip arthroplasty as well as fracture of the femur or patients immobile prior to the scan.

Moreover patients with tumors of the lower extremity, scoliosis and degenerative alterations of the spine, asymmetry of the pelvis or prone position during scanning were excluded from the study.

2.2. CT-scans

Patients were scanned in supine position using a Toshiba Aquilion 64® and Philips Mx8000 IDT 16® Scanner creating slice thicknesses from 3 mm to 5 mm at a Gantry inclination of 0°. Pixel size ranged from 0.583 mm × 0.583 mm to 0.885 mm × 0.885 mm.

CT data was analyzed using Vitrea 2® (Vital Images, Minnesota, USA), ImageJ and GnuPlot (both Public Domain).

Both the right and the left side were analyzed. Average values for each patient’s GMV and FO were calculated yielding 102 comparable sets of measurements.

2.2.1. Muscle measurement

Cross-sectional areas (CSA) [cm²] of the GM were traced on each slice using a Vitrea2® CT software package. Muscle Volumes (GMV) [cm³] were automatically calculated by Vitrea 2® soft ware package as the sum of each CSA multiplied by the width of the slice (Fig. 2a and b).

Bony landmarks were marked in the two-dimensional (2D) slices to avoid rounding errors due to the 3D reconstruction done by a picture processing software.
2.2.2. Hip Geometry Measurement

**Centre of femoral head (CFH):** Coordinates of the middle of the femoral head, marked in the slices the greatest diameter was pictured, were recorded (Fig. 3).

**Femoral axis (FA):** The FA was calculated as line of best fit of the centres of the ellipses that were automatically fitted to the inner femoral cortex on each slide (Fig. 4).

**Femoral offset (FO):** FO was calculated as the length of the vector perpendicular to the FA from the FA to the CFH (Fig. 4). Body weight lever arm (BWLA) was calculated as half of the distance measured between the centres of the femoral heads (Fig. 5).

2.3. Statistical analysis

Data was analyzed using the Kolmogorov–Smirnov Z-test and Levene test for normal distribution and homogeneity of the variances. Correlation analyses as well as scatter plots were performed for demographic data and the obtained measurements of FO, BWLA and GMV. Pearson and Spearman-Rho analyses were used for parametric and non-parametric data as appropriate. The best combination of anatomic and demographic data for predicting the GM volume was evaluated using multiple linear regression analysis. Single correlations were then scatter plotted to screen for non-linear correlations between GMV and the variables included. For reasons of better interpretation variables were centered at the mean before taken into the model. Multicollinearity was investigated by calculation of the variance inflation factor. A p-value less than 0.05 was considered to be significant. Data analysis was performed using SPSS statistical package 18.0 (SPSS Inc., Chicago, IL).

3. Results

The analysis of the demographic data collected showed a normal distribution for age, height and bodyweight (Table 1). The mean GMV obtained was 289 ± 72 cm³. The mean FO measured was 4.14 ± 0.55 cm. The mean BWLA obtained was 8.88 ± 0.4 cm. Data is summarized in Table 2.

All hip geometry data and demographic data except for age were significantly correlated with the GMV. The obtained correlation coefficients and p-values are listed in Table 3.

To assess the contributions of demographic data as well as hip geometry to the volume of the GMV linear regression analysis was applied to those correlating significantly.

We then investigated the obtained model for multicollinearity and type of correlations. For height yielding a variance inflation factor (VIF) of 2.93 the variable was excluded from the model. In scatter plots for GMV and parametric demographic data as well as for GMV and hip geometry (FO, BWLA) no indication for non-linearity was observed.

### Table 2

Hip geometry data and gluteus medius volume (GMV) for the population investigated. Femoral offset (FO); body weight lever arm (BWLA); number of data sets (n); and standard deviation (SD).

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Range (min–max)</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMV [cm³]</td>
<td>102</td>
<td>142–466</td>
<td>289</td>
<td>72</td>
</tr>
<tr>
<td>FO [cm]</td>
<td>102</td>
<td>2.85–5.40</td>
<td>4.14</td>
<td>0.55</td>
</tr>
<tr>
<td>BWLA [cm]</td>
<td>102</td>
<td>7.83–9.85</td>
<td>8.88</td>
<td>0.4</td>
</tr>
</tbody>
</table>
The formula gained from the regression analysis allows an estimation of the GMV on the basis of the hip geometry and demographic data. Thereby reference values to individually set the goals for rehabilitation after THA and FO reconstruction in terms of muscle volume regenera
can be approximated with good accuracy. During the course of rehabilitation the formula can be used to evaluate the progress and the effectiveness of rehabili-
tion programs. Further the formula can help deﬁne endpoints at which the “physiological” muscle mass is regained. Still, we have to men-
tion that the $R^2$ value may give an over-optimistic impression of accuracy of prediction and the model has yet not been validated on an external data set.

4.1. Muscle volume

Our results of GMV obtained from 3D-CT volume reconstruction appear to be slightly lower than those obtained in previous studies investigating GMV within a control group without hip pathology (Grimaldi et al., 2009). In that study changes in GMV were measured according to different stages (mild, advanced, control) of unilat
eral degenerative hip joint disease. No signiﬁcant asymme-
tries of GMV were observed within that study control group as well as in our study. The assessed differences in the overall volume might be due to the higher age (+6.2y) within the population investigated and the by far smaller sample size in the cited study compared to our study (12 vs. 204).

4.2. Hip joint geometry

The FO measured within our population is consistent with that obtained in studies using methods based on 3D-CT scans for measurements (Husmann et al., 1997; Sariali et al., 2009). The fact that there are no differences between the values measured by Husmann and Sariali compared to our measurements is quite remarkable since the populations investigated in those studies suffered from idiopathic osteoarthritis although the age-average within the populations investigated is almost the same (62 vs. 58.5 in our study) (Husmann et al., 1997).

4.3. Relations between muscle volume and joint geometry

The ﬁndings that FO was indirectly (negatively) taken into account in the linear regression model to predict the GMV was not expected in the ﬁrst place. Due to the positive correlations between the size of the pelvis (FO, BWLA) and the size of the patient (height, bodyweight) a positive correlation between the GMV and FO was found (Table 3). Such positive correlations resulted in partial mul-
ticollinearity of height and other parameters. Subsequently height was not included in the regression model.

Going more into detail, considering the fulcrum between the FO and the BWLA (Traina et al., 2009) we assumed that by increasing the lever arm of the GM (through increasing FO) the effectiveness of the abduction force exerted by the GM would rise and therefore

### Table 3

<table>
<thead>
<tr>
<th>Coefficients and $p$-values for gluteus medius volume (GMV) and demographic data as well as hip joint geometry are shown.</th>
<th>Corr. coeff.</th>
<th>p-Value</th>
<th>p-Value</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>Bodyweight</td>
<td>Age</td>
<td>Gender</td>
<td>FO</td>
</tr>
<tr>
<td>GMV</td>
<td>Corr. coeff.</td>
<td>0.670$^a$</td>
<td>0.710$^a$</td>
<td>0.04$^a$</td>
</tr>
<tr>
<td>p-Value</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.068</td>
<td>&lt;0.0001</td>
</tr>
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* Pearson coefficient.

In the recalculated model a coefﬁcient of determination $R^2 = 0.681$ ($p < 0.0001$) was obtained with the combination of the hip geometry data and demographic parameters. Details of the regression model are summarized in Table 4.

Thereby a formula to calculate GMV from FO, BWLA and demographic data was derived:

$$GMV = \frac{\text{Bodyweight}[\text{kg}] \times 2.2 + \text{BWLA}[\text{cm}] \times 5.7}{\text{FO}[\text{cm}] \times 18.8 + 260.2} + \left\{ \begin{array}{l}
\text{male : } + 56.1 \\
\text{female : } + 0
\end{array} \right.$$ 

The formula derived suggests that approximately 70% of the variability of the GMV can be explained by demographics and hip geometry (Fig. 6).

4. Discussion

In the current study we analyzed the volume of the GM, hip joint geometry (femoral offset, body weight lever arm) and possible correlations of these parameters within a group of patients without hip pathology. We found the volumes of the GM to be signiﬁcantly correlated to hip joint geometry. Taking demographic data into account in the linear regression model was obtained explaining approximately 70% of the variability of GMV.

A cornerstone of the hypothesis of this work is the commonly accepted correlation between muscle volume and muscle force (Tonson et al., 2008). Still we have to keep in mind that muscle volume is not the stand-alone parameter for muscle force and that individual fractions of intramuscular fat content as well as neuro-
physiological circumstances may cause individual variability in this relation. Also motor control changes and changes of the ﬁbre type composition of the pelvic muscles observed in patients suffering from osteoarthritis may alter the individual correlation of muscle volume and force and its individual variability (Eimre et al., 2006; Chumanov et al., 2008). These individual variations have been shown to be also gender related and may possibly explain the inﬂuence of gender in the obtained formula.

A limitation of this study is a possible inaccuracy in determining the femoral axis because only the proximal part of the femoral shaft was depicted in the CT-scans. That could have led to incorrect calculations of FO. Nevertheless the absolute values obtained for FO are rather consistent with those found in other 3D-CT studies.
reduce the amount of muscle “necessary”. A negative coefficient would be the consequence. In the regression model in which the specific contribution of each parameter to the variation of the dependent variable is shown, such a negative coefficient between GMV and FO was found.

An explanation for such a negative coefficient could be found taking musculoskeletal development into account. Bony structures adapt to muscular strains (Perka et al., 2005). As the proximal femur, and thereby the FO develops during skeletal growth it is strongly influenced by the strains and excursions occurring during hip joint motion at the developmental period. Hip joint motion is controlled also and particularly by the GM. Due to the parallel development of those two structures lower forces exerted by a smaller GM could allow more growth in the lateral direction and thereby favoring the development of a greater FO. Such relations can, for example, be observed when looking at the hip geometry of high hip displacement (HHD) after developmental hip dysplasia (Carl et al., 2002). Femoral anatomy in HHD patients includes a high caput–collum–diaphyseal angle resulting in small FO as well as an elongated proximal femur. This femoral elongation could be caused by a lack of resistance during growth due to a lack of contact to the acetabular cup. In converse argument a large GM exerting a large axial force on the femoral neck could keep the axial growth rate lower compared to the situation where a smaller axial force by a smaller GM is exerted. This could then lead to a hand in hand development of GM and FO.

Further, such a negative correlation between FO and GMV can be used to explain the observations made in patients after THA. Asayama et al. found optimized hip abductor function after a slight increase of FO (Asayama et al., 2005) as well as Yamaguchi et al. (2004) and McGroty et al. (1995) who observed abductor strength to correlate positively with FO and the abductor lever arm, respectively.

5. Conclusion

The formula derived from the regression analysis allows an estimation of the GMV on the basis of the FO and demographic data. The possibility of individually determining index values for the GMV may be beneficial to the evaluation of muscle rehabilitation after THA and could thereby help to improve the effectiveness of such rehabilitation programs by setting individual goals for each patient.

Moreover the association between GMV hip joint geometry and demographic data found in this study may reflect a hand in hand development of FO and GM during growth and a continuous functional relationship between those two variables thereafter. Functional observations so far made after THA can be explained by the negative correlation between FO and GMV reported in our study.

References


