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Biomechanical analysis of various operative hip joint rotation center shifts

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Summary. A mathematical model was used to evaluate the mechanical situation after various operative shifts of the hip joint rotation center. It was concluded that while performing different pelvic osteotomies and the total hip replacement the hip joint rotation center should be shifted as far medially as is technically possible to reduce the magnitude of the hip joint contact force. By contrast, lateralization of the hip joint rotation center strongly increases the magnitude of the hip joint contact force; therefore this should be avoided whenever possible. The superior shift of the hip joint rotation center decreases the strength of the patient's hip abductor muscles and must therefore also be avoided. The inferior shift of the hip joint rotation center is favorable because it increases the strength of the patient's hip abductor muscles.

Hip joint rotation center (RC) shifts may occur after different pelvic osteotomies, for example, after Chiari's or periacetabular osteotomy [4, 6], and after total hip replacement [2]. RC shifts are possible in the mediolateral, superiorinferior, and anterioposterior directions. The aim of the present work was to study the influence of such operative RC shifts on the postoperative magnitude of the hip joint contact force $\vec{R}$ and on the postoperative strength of the patient's hip abductor muscles.

In the present analysis of different RC shifts it is assumed that development of primary coxarthrosis is accelerated by the high hip joint contact pressure [1]. High hip joint contact pressure may be a consequence of a high value of the hip joint contact force, in addition to a small hip joint contact area. Therefore it is proposed that reduction in the magnitude of hip joint contact force (R) after operative interventions is favorable [4, 6]. However, the criterion that the hip joint contact force is reduced is not sufficient to estimate the overall efficiency of the surgical intervention in the hip. After different operative RC shifts, some muscle attachments are translocated, and therefore the lengths of these muscles are changed. As a consequence, the maximal available muscle forces of these muscles are also changed [5]. This could be important because the vector sum of the maximal available hip abductor muscle forces ($\vec{F}_{av}$) could be changed considerably after the operation. When the magnitude of $\vec{F}_{av}$ becomes smaller than the magnitude of the the vector sum of the hip abductor muscle forces required to perform the mechanical equilibrium of the body (required resultant hip muscle force $\vec{F}_{req}$), it is proposed that lurch appears, and Trendelenburg's signs may even become positive.

Therefore in this study a comprehensive biomechanical study of the lateral, medial, superior, inferior, anterior, and posterior RC shifts was performed which considers the postoperative values of the required resultant hip muscle force, the maximal available resultant hip muscle force, and the hip joint contact force.

Methods

A simple static three-dimensional model of an adult human hip in one-legged stance was used to calculate the hip joint contact force $\vec{R}$ and the required resultant hip muscle force $\vec{F}_{req}$. The model is described in detail by Iglič et al. [4]; therefore only the major characteristics of the model are given here.

In the model used, the muscles of piriformis, gluteus medius, gluteus minimus, rectus fomoris, and tensor fasciae latae are included as these muscles are the most important at determining the one-legged stance [1]. Since the gluteus minimus and gluteus medius are attached to the pelvis in a rather large area, each of these two muscles are divided into three parts: anterior, middle, and posterior. Thus nine muscles are included in the model. It is assumed that the force of an individual muscles acts along straight line connecting the attachment point of the muscle origin on the pelvis and the corresponding attachment point of the muscle insertion on the femur. The forces $\vec{R}$ and $\vec{F}_{req}$ are calculated by solving the equations of mechanical equilibrium for the pelvis and loaded lower extremity [4].

The maximal available resultant hip muscle force $\vec{F}_{av}$ is the vector sum of the maximal available forces of individual muscles $\vec{F}_{av,i}$. The magnitude of the maximal available force of an individual muscle $F_{av,i}$ is estimated in the present study using the approximative linearized relation:

$$F_{av,i} = \sigma_{av} \cdot A_i \cdot [K_1 \cdot (l_i/l_{i,r}) + K_2]$$

where $K_1 = 1.25$, $K_2 = -0.5$ [5], $l_{i,r}$ is the reference length of the ith muscle before the RC shift, l_i is the actual length of the ith mus-

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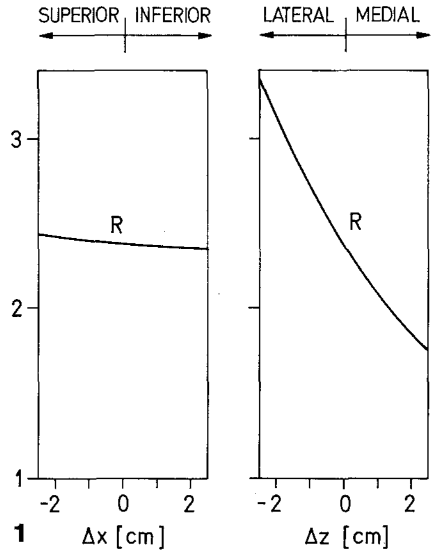

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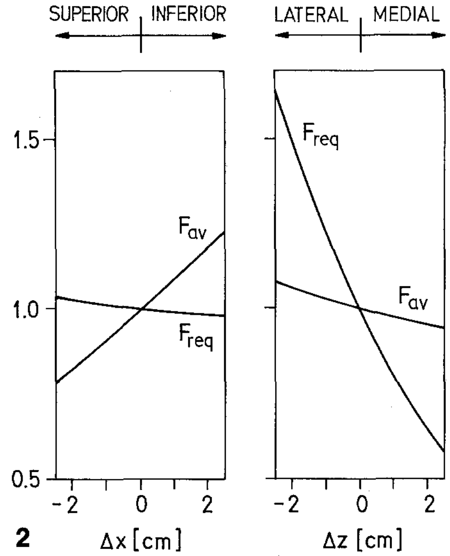

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Fig. 1. The dependencies of the magnitude of the hip joint contact force *(R)* on the the hip joint rotation center shifts in the superior ($\Delta x < 0$), inferior ($\Delta x > 0$), medial ($\Delta z > 0$), and lateral ($\Delta z < 0$) directions. All the calculated values of R are normalized with respect to the magnitude of the body weight force

Fig. 2. The dependencies of the relative magnitudes of the required resultant hip abductor muscle force [F_{req}/F_{req} ($\Delta x = \Delta z = 0$)] and the maximal available resultant hip abductor muscle force [F_{av}/F_{av} ($\Delta x = \Delta z = 0$)] on the hip joint rotation shifts in the in the superior ($\Delta x < 0$), inferior ($\Delta x > 0$), medial ($\Delta z > 0$), and lateral ($\Delta z < 0$) directions

cle after the RC shift, σ_{av} is the maximal available muscle tension which determines the upper bound of the muscle force, and A_i is the mean physiological cross-sectional area of the individual muscle. The values of A_i used were determined from the data of Pedotti and Iglič et al. [4, 5]. The validity of the equation is limited by the assumption that during the one-legged stance the hip muscles operate on the ascending region of their force-length curve (see also Pedotti [5]).

In calculating $\vec{F}_{req}$, $\vec{F}_{av}$, and $\vec{R}$ the variation of the RC position in the mediolateral (Δz), anterioposterior (Δy), and superioinferior (Δx) directions are simulated by variation of the coordinates of the muscle attachment points and by variation of the interhip distance [4]. The reference values of the coordiantes of muscle attachment points are taken from Dostal and Andrews [3].

Results

The results are interpreted in view of the dependencies of the magnitudes of the hip joint contact force $\vec{R}$ (R), the required resultant hip muscle force $\vec{F}_{req}$ (F_{req}), and the maximal available resultant hip muscle force $\vec{F}_{av}$ (F_{av}) on the RC shifts. We found that the RC shift in the anterioposterior direction has very little influence on R, F_{req}, and F_{av}, whereas RC shifts in the mediolateral and superioinferior directions have a significant influence. The continuous dependencies of R on the mediolateral and superiorinferior RC shift are presented in Fig. 1 while the continuous dependencies of F_{req} and F_{av} on the mediolateral and superiorinferior RC shift are presented in Fig. 2.

Discussion and conclusions

This shows that the medialization of RC diminishes the magnitude of the required resultant hip muscle force (F_{req}), the magnitude of the hip joint contact force (R), and the magnitude of the maximal available resultant hip muscle force (F_{av}). However, the decrease in F_{req} is much more pronounced than the corresponding decrease in F_{av} (see Fig. 2). Therefore, the distinctive decrease in F_{req} after the medialization of RC is favorable because in this way the difference between F_{av} and F_{req} is increased, which means that the hip abductor muscles' strength is also increased. The medialization of RC is also favorable because the medial RC shift may considerably reduce the hip joint contact force (see Fig. 1).

The lateral RC shift increases F_{req}, R, and F_{av}. However, the increase in F_{req} is much more pronounced that the corresponding increase in F_{av} (see Fig. 2). Namely, with lateralization of RC the value of F_{req} can approach the value of F_{av} or even exceed it, leading to lurch or even a positive Trendelenburg's sign. The lateralization of RC is also unfavorable because the lateral RC shift increases R. It can therefore be concluded that while performing differing operative interventions, the lateralization of RC should be avoided if possible.

It was further calculated in the present work that the inferior RC shift may slightly reduce F_{req} and increase F_{av}. In this way the strength of the hip abductor muscles is increased, which is favorable regarding Trendelenburg's sign and lurch after the operation.

On the other hand, the superior shift in RC is unfavorable because it simultaneously increase F_{req} and diminishes F_{av}, which is the most unfavorable combination (see Fig. 2). The decrease in F_{av} after the superior RC shift could be important because F_{av} may be reduced to such extent that it becomes smaller than F_{req}. As a consequence the lurch may appear or Trendelenburg's sign could even become positive after the operation. Therefore it can be recommended regarding the postoperative strength of the hip abductor muscles that the superior RC shift should be avoided if possible.

On the basis of the present results it can therefore be concluded that while performing different pelvic osteotomies and total hip replacement the hip joint rotation center should be shifted as far medially as is technically possible in order to reduce the magnitude of the hip joint contact force. On the other hand, the lateralization of RC should be avoided whenever possible because it strongly increases the magnitude of the hip joint contact force. The superior RC shift decreases the strength of the patient's hip abductor muscles, and therefore it must also be avoided. The inferior hip joint rotation center shift is favorable because it increases the strength of the patient's hip abductor muscles.

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