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Calculation of impingement-free combined cup and stem alignments based on the patient-specific pelvic tilt

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ABSTRACT

Proper cup alignment is crucial in total hip arthroplasty for reducing impingement risks, dislocations and wear. The Lewinnek "safe zone" is often used in clinical routine. This safe zone does not consider functional aspects and dislocation can occur even when the cup is oriented within the safe zone. Functional safe zones based on the hip range of motion (ROM) were introduced but are not commonly used in clinical routine. The reason might be that these methods are time-consuming due to complex simulations. A relatively fast method based on analytical mathematical formulas was proposed, but it is difficult to consider arbitrary motion. This work introduces an efficient algorithm for calculating a patient-specific target zone based on the target ROM which can consider any set of motions. The method is based on matrix transformations and trigonometric formulas. The resulting target zone which contains all impingement-free cup orientations is dependent on the patient-specific pelvic tilt, the 3D angular neck and stem orientation within the femur, and the technical prosthesis ROM. This method could be integrated into computer-assisted preoperative planning and intra-operative navigation tools. As pelvic tilt and stem orientation influence the optimal cup orientation they need to be acquired from the patient to derive a patient-specific ROM-based target zone.

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1. Introduction

Proper acetabular and femoral component design, position and orientation are of major importance in total hip arthroplasty for a long prosthesis lifespan. Despite high clinical success rates, complications, such as impingement, dislocations, accelerated wear and loosening, still occur (Bozic et al., 2009; Pivec et al., 2012; Rajaee et al., 2018; Seagrave et al., 2017; Ulrich et al., 2008). The Lewinnek safe zone (Lewinnek et al., 1978), which suggests a radiographic inclination of $40° ± 10°$ and a radiographic anteversion of $15° ± 10°$ relative to the anterior pelvic plane (APP) (Jaramaz et al., 1998), is often considered as the optimal cup orientation. However, it has been shown that dislocations occur also even when the cup is orientated according to the safe zone (e.g. Abdel et al., 2016). Numerous studies addressing the optimal cup orientation exist. The cup orientations of dislocated cases are often compared to a control group (Biedermann et al., 2005; Dorr et al., 1983; Jolles et al., 2002; Lewinnek et al., 1978; Murphy et al., 2014; Seagrave

et al., 2017). The results depend on the cohort and it is a "safe zone" for the average patient.

There is no single unified safe zone referring to the APP that can be applied to all patients due to high variations of the pelvic tilt in the standing position (DiGioia et al., 2006; Kanawade et al., 2014; Lembeck et al., 2005; Nishihara et al., 2003) which influences the functional cup orientation (Babisch et al., 2008; Lembeck et al., 2005). Cup implanted within a certain safe zone in the supine position can be mal-orientated when examined in the standing position (Au et al., 2014; Tiberi et al., 2015). Nomograms (Babisch et al., 2008), linear correlations factors (Lembeck et al., 2005) and 3D transformation methods (Chen et al., 2006) were proposed for correcting the cup orientation in order to achieve proper functional cup alignment.

Other studies incorporate functional aspects such as the range of motion (ROM) (Barrack et al., 2001; Elkins et al., 2015; McCollum and Gray, 1990; Pedersen et al., 2005; Widmer and Zurfluh, 2004; Yoshimine, 2006). Impingement between the components is determined and impingement-free cup orientations are derived. The results depend on the defined target ROM, the implant component placement, such as the femoral antetorsion or combined anteversion (Elkins et al., 2015; Widmer and Zurfluh, 2004; Yoshimine, 2006), and prosthesis-specific

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parameters such as the head/neck ratio (Barrack et al., 2001; Elkins et al., 2015) and the cup and neck design (Barrack et al., 2001).

The problem of including the methods described in literature into the clinical workflow is not fully solved. Methods calculating suitable cup orientations based on the ROM using three-dimensional (3D) computer simulation (Widmer and Zurfluh, 2004) or finite element simulation (Elkins et al., 2015) might not be suitable for clinical routine as they might be time-consuming and complex. By contrast, the method described by Yoshimine and Ginbayashi (Yoshimine and Ginbayashi, 2002) is fast because it is an analytical mathematical solution, however, an extension to considering arbitrary motion is not straightforward.

A ROM-based target zone calculation algorithm which does not rely on 3D simulations and collision detection but does integrate arbitrary motion is introduced in this work. This approach is suitable for being integrated into computer-assisted total hip arthroplasty (THA) planning and navigation systems requiring only few patient-specific input parameters. A sensitivity analysis was performed to determine which parameters should be acquired from each individual patient for planning.

2. Materials and methods

Prosthetic impingement is defined as the collision of the femoral neck with the rim of the cup. (Yoshimine, 2005) pointed out that prosthetic impingement depends on the technical ROM of the prosthesis, cup orientation (inclination and anteversion), and the neck orientation. The technical ROM is defined by the cup shape and the head/neck ratio (Yoshimine, 2005). The cup orientation is influenced by the pelvic tilt (e.g. Babisch et al., 2008), the functional neck orientation is determined by the orientation of the neck relative to the stem, the orientation of the stem relative to the femur and the motion of the femur relative to the body coordinate system. Based on these parameters, all impingement-free combined cup and stem orientations, the so-called prosthetic ROM-based target zone is calculated. An overview of the algorithm developed is shown in Fig. 1.
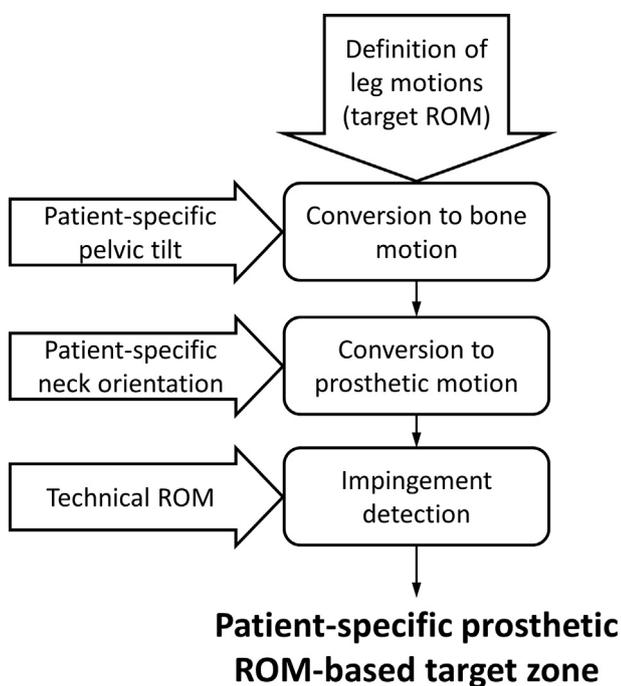

Fig. 1. Overall workflow for calculating ROM-based patient-specific target zone.

The convention recommended by the International Society of Biomechanics (ISB) (Wu et al., 2002) is used for defining the pelvic coordinate systems and the related motions. The origin of the coordinate system is in the center of rotation. The pelvic coordinate system is defined by the X-axis pointing towards anterior, Y-axis towards superior and Z-axis towards lateral. The femoral coordinate system is defined by the x, y, and z-axis in the same manner. Only the right hip is considered. Left hips have to be mirrored prior to computation. The amount of flexion/extension (f) is the angular rotation around the Z-axis (fixed to pelvis), internal/external rotation (r) is around the y-axis (fixed to femur) and adduction/abduction (a) is around the axis perpendicular to y and Z which is a floating axis. Flexion, adduction and internal rotation have positive signs.

For each combination of f, a and r, a rotation matrix R can be constructed for describing the femur orientation relative to the pelvic coordinate system (*femur2pelvis*) as follows:

$$
\begin{aligned}
Femur_{\text{transformed}} &= R_{femur2pelvis} \cdot Femur_{\text{neutral}} \\
&= R_Z(f) \cdot R_X(a) \cdot R_Y(r) \cdot Femur_{\text{neutral}} \\
&= R_Z(f) \cdot R_X(a) \cdot Femur_{r\ \text{applied}} \quad (1) \\
&= R_Z(f) \cdot Femur_{a\ \text{and}\ r\ \text{applied}} \\
&= Femur_{f,a\ \text{and}\ r\ \text{applied}}
\end{aligned}
$$

$$
R_Z(f) = \begin{pmatrix} \cos(f) & -\sin(f) & 0 \\ \sin(f) & \cos(f) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2)
$$

$$
R_X(a) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(a) & -\sin(a) \\ 0 & \sin(a) & \cos(a) \end{pmatrix} \quad (3)
$$

$$
R_Y(r) = \begin{pmatrix} \cos(r) & 0 & \sin(r) \\ 0 & 1 & 0 \\ -\sin(r) & 0 & \cos(r) \end{pmatrix} \quad (4)
$$

When starting from the neutral position, internal/external rotation is applied first. The femoral y-axis coincides with the pelvic Y-axis. The matrix $R_Y(r)$ describes a rotation around the Y-axis by the angle r. Next, adduction/abduction is applied. The axis perpendicular to y and Z coincides with the pelvic X-axis since flexion/extension has not been performed yet. Lastly, flexion around the Z-axis is applied.

The ISB recommendation originally defines the orientation of the femur relative to the pelvis. This convention is analogously applied for also describing the orientation of the leg relative to the body coordinate system (R_{leg2body}) and the femoral neck orientation relative to the cup coordinate system (R_{neck2cup}). R_{A2B} is the rotation matrix defining the orientation of A relative to the coordinate system of B.

A target ROM, consisting of multiple leg orientations $R_{\text{leg2body},n}$ with $n = 1, 2, \cdots, N$ has to be defined. The conversion into the bone movements is as follows:

$$
R_{\text{femur2pelvis},n} = R_{\text{pelvis2body}}^{-1} \cdot R_{\text{leg2body},n} \cdot R_{\text{femur2leg}} \quad (5)
$$

R^{-1} denotes the inverse transformation of R. It is assumed that the transformation of the pelvis relative to the body coordinate system is determined by the pelvic tilt only

$$
R_{\text{pelvis2body}} = R_Z(-\phi_{\text{tilt}}) = \begin{pmatrix} \cos(-\phi_{\text{tilt}}) & -\sin(-\phi_{\text{tilt}}) & 0 \\ \sin(-\phi_{\text{tilt}}) & \cos(-\phi_{\text{tilt}}) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (6)
$$

and that the coordinate system of the leg is the same as the coordinate system of the femur

$$R_{\text{femur2leg}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{7}$$

Next, the bony movements are converted to the prosthesis movements:

$$R_{\text{neck2cup},n,\phi_{\text{incl}},\phi_{\text{ant}}} = R_{\text{cup2pelvis},\phi_{\text{incl}},\phi_{\text{ant}}}^{-1} \cdot R_{\text{femur2pelvis},n} \cdot R_{\text{neck2femur}} \tag{8}$$

Murray's radiographic definition (Murray, 1993) is used to characterize the orientation of the cup $R_{\text{cup2pelvis},\phi_{\text{incl}},\phi_{\text{ant}}}$ and is calculated as follows:

$$R_{\text{cup2pelvis},\phi_{\text{incl}},\phi_{\text{ant}}} = R_X(-\phi_{\text{incl}}) \cdot R_Z(\phi_{\text{ant}}) \tag{9}$$

Note that by applying the anteversion first, the axis usually used for radiographic anteversion coincides with the Z-axis. The cup orientation is referenced to the pelvic coordinate system.

The neck orientation relative to the femur coordinate system was calculated using the stem orientation (antetorsion, adduction and flexion) and the neck-shaft angle (CCD angle). The order of rotation had to be defined. The starting neck orientation is directed towards the negative Y direction. First, a rotation around X is applied. The angle is defined by the stem adduction and the neck-shaft angle. Then, antetorsion around the Y-axis is applied.

Lastly, the neck is rotated around the Z axis by the amount of stem flexion.

$$R_{\text{neck2femur}} = R_Z(-\phi_{\text{stemFlex}}) \cdot R_Y(-\phi_{\text{antetorsion}}) \\ \cdot R_X(-(180° - \phi_{\text{CCD}} - \phi_{\text{stemAdd}})) \tag{10}$$

Note that this and any other order of rotation has the effect that the applied rotation angles differ from the angles that can be measured in the projected neck axis which is usually used for measuring antetorsion, adduction and flexion.

The prosthetic movement is then compared to the technical ROM ϑ which can be calculated as follows (Yoshimine and Ginbayashi, 2002):

$$\vartheta = A - 2 \cdot \sin^{-1}\left(\frac{1}{r_{head}/r_{neck}}\right) \tag{11}$$

A is the cup opening angle, r_{head} and r_{neck} are the radii of the head and the neck, respectively. A 2D mapping of the 3D motion sphere was developed for calculating the distance of the neck to the impingement point (see Fig. 2). For each cup orientation, the minimal distance to impingement is calculated as follows:

$$R_{\text{neck2cup},n,\phi_{\text{incl}},\phi_{\text{ant}}} = \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix} \tag{12}$$

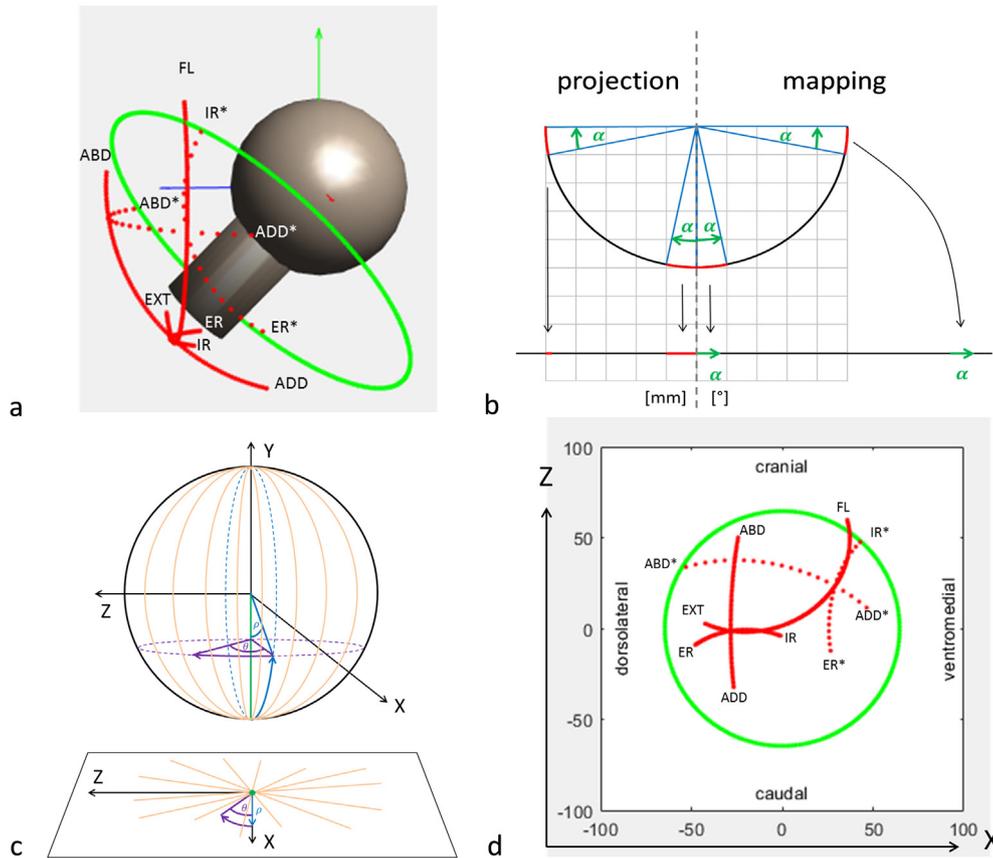$$\rho_{n,\phi_{\text{incl}},\phi_{\text{ant}}} = \arccos(R_{22}) \tag{13}$$

Fig. 2. Mapping of the femoral neck movement relative to the cup from a 3D sphere onto a 2D plane. a: Movement of the neck axis end points (red) relative to the cup limits (green) for leg movements in physiological planes. * and the dotted curves denote motions in 90° of flexion. b: Comparison between projection and mapping. c: Method for unfolding the 3D spherical surface onto a 2D plane. d: Mapped version of a. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$\theta_{n,\phi_{incl},\phi_{ant}} = -\text{atan2}(R_{32}, -R_{12})   \tag{14}$$

$$d_n(\phi_{incl}, \phi_{ant}) = \frac{\vartheta}{2} - \rho_{n,\phi_{incl},\phi_{ant}}   \tag{15}$$

$$d_{min}(\phi_{incl}, \phi_{ant}) = \min_n d_n(\phi_{incl}, \phi_{ant}) \begin{array}{l} > 0 \rightarrow \text{impingement-free} \\ \leq 0 \rightarrow \text{impingement} \end{array}   \tag{16}$$

Please refer to the Supplementary materials for the derivation of these equations.

All impingement-free cup orientations are classified for being within the target zone. An example is shown in Fig. 3 and its calculation can be found in the Supplementary materials. Note that Eq. (14) is not needed for target zone calculation. It is only used for visualization and will be needed for extending the method to be used for incorporating non-symmetric cups and necks.
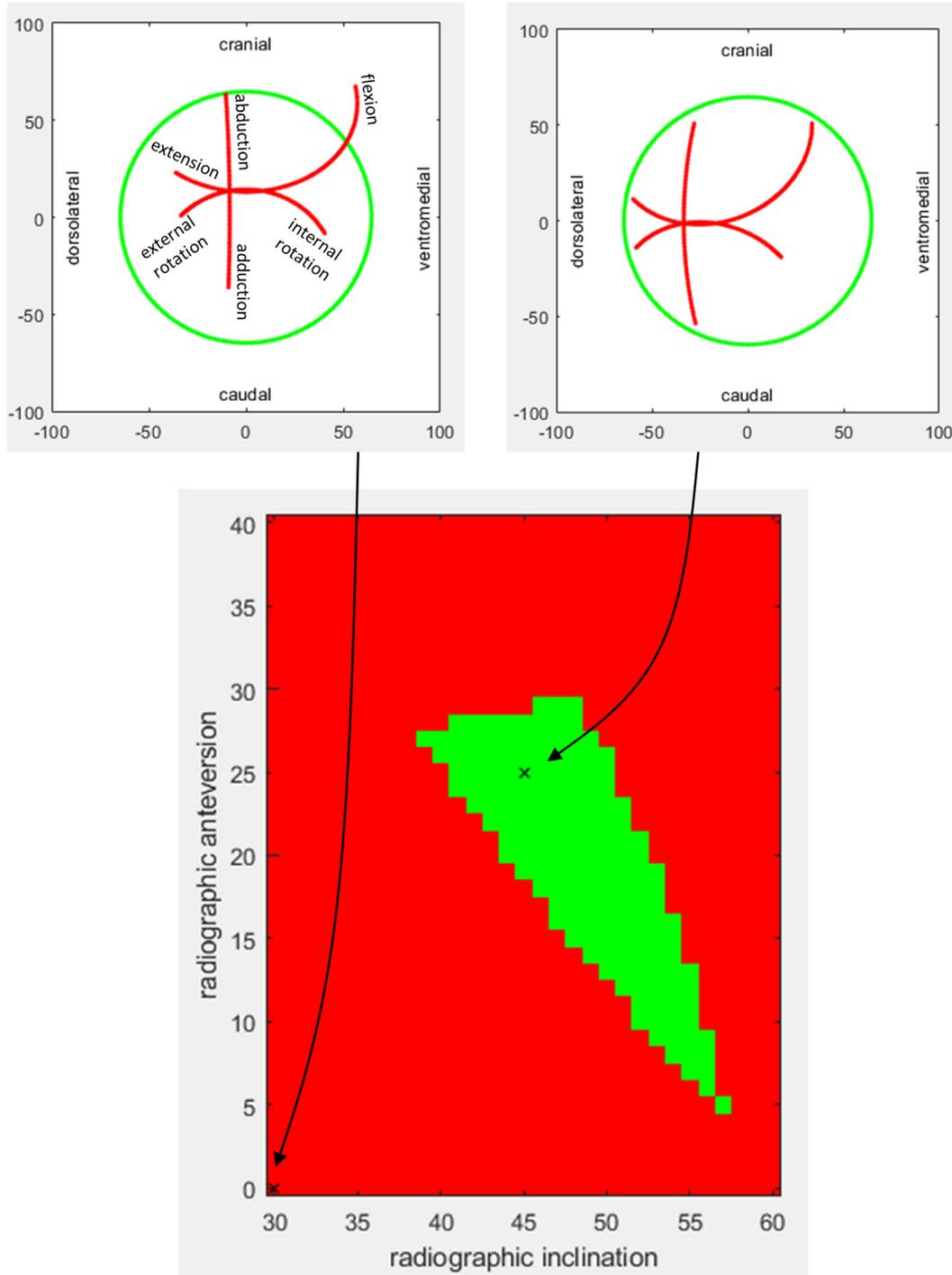

Fig. 3. Example for calculating the target zone. The left image shows the relative neck ROM for a cup orientation of 30° of inclination and 0° of anteversion. Some points of the neck ROM are outside the cup limits, therefore, the corresponding cup orientation is marked as "outside the target zone." The right image shows the relative neck ROM for a cup orientation of 45° of inclination and 25° of anteversion. All points of the neck ROM are inside the cup limits and the corresponding orientation is marked as "inside the target zone."

Table 1
Parameters for comparing the resulting target zone with literature.

Parameter	Widmer and Zurfluh (2004)	Yoshimine (2005)	Yoshimine (2006)
Inclination	20° to 70°	0° to 70°	45°
Anteversion	−20° to 50°	−10° to 45°	0° to 60°
Antetorsion	0°, 15°, 30°	20°	−10° to 40°
Neck-shaft angle	130°	135°	135°
Stem flexion	3°	0°	0°
Stem adduction	5°	7°	7°
Head radius	14 mm	15.68 mm ($\vartheta = 135°$)	15.68 mm ($\vartheta = 135°$)
		12 mm ($\vartheta = 120°$)	
		10.46 mm ($\vartheta = 110°$)	
Neck radius	6 mm	6 mm	6 mm
Cup opening plane	180°	180°	180°
Flexion	130°	110°	110°
Extension	40°	30°	30°
Adduction	50°	–	–
Abduction	50°	–	–
Internal rotation	80°	30° (at 90° flexion)	30° (at 90° flexion)
External rotation	40°	40°	40°

Table 2
Exemplary set of motions/target ROM derived from literature.

							at 90° flexion			
Publication	FL	EXT	ADD	ABD	IR	ER	ADD	ABD	IR	ER
Widmer and Zurfluh (2004)	130	40	50	50	80	40	–	–	–	–
Schuenke et al. (2010)	140	20	30	50	40	30	20	80	40	50

Extracted from Turley et al. (2011)
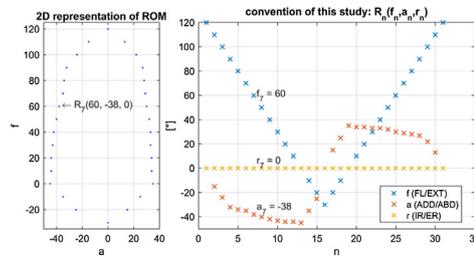
Extracted from Nadzadi et al. (2003)
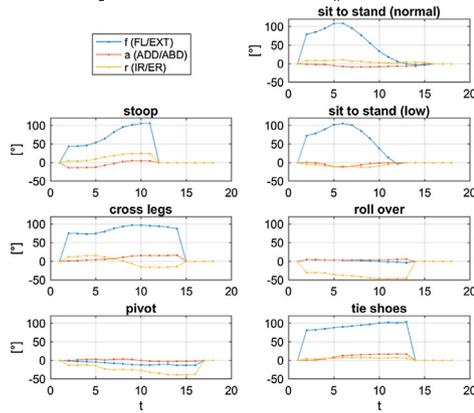
2.1. Evaluation methods

The mathematical formulas and their implementation were validated by comparing the resulting target zone with the ones from Widmer and Zurfluh (2004), Yoshimine (2005) and Yoshimine (2006) using the corresponding input data (Table 1). The reference values of the resulting target zones were extracted manually from the published graphs and compared to the results from the proposed method. The anatomic anteversion values derived from (Yoshimine, 2006) were converted into the radiographic anteversion using Murray's equations (Murray, 1993).

The computing time was recorded for calculating the target zone for the ROM specified by Widmer and Zurfluh (2004) for 3621 cup orientations (51 inclinations * 71 anteversions) and a single value for all other parameters. The computing was carried out using MATLAB R2017b on a 64-bit Windows PC with an Intel Core i7 processor.

2.2. Sensitivity analysis

Sensitivity analyses were performed to investigate the effect of the input parameters on the target zone.

2.2.1. Target ROM

The results depend on the definition of the leg to body target ROM. A literature review showed that suitable definitions for the
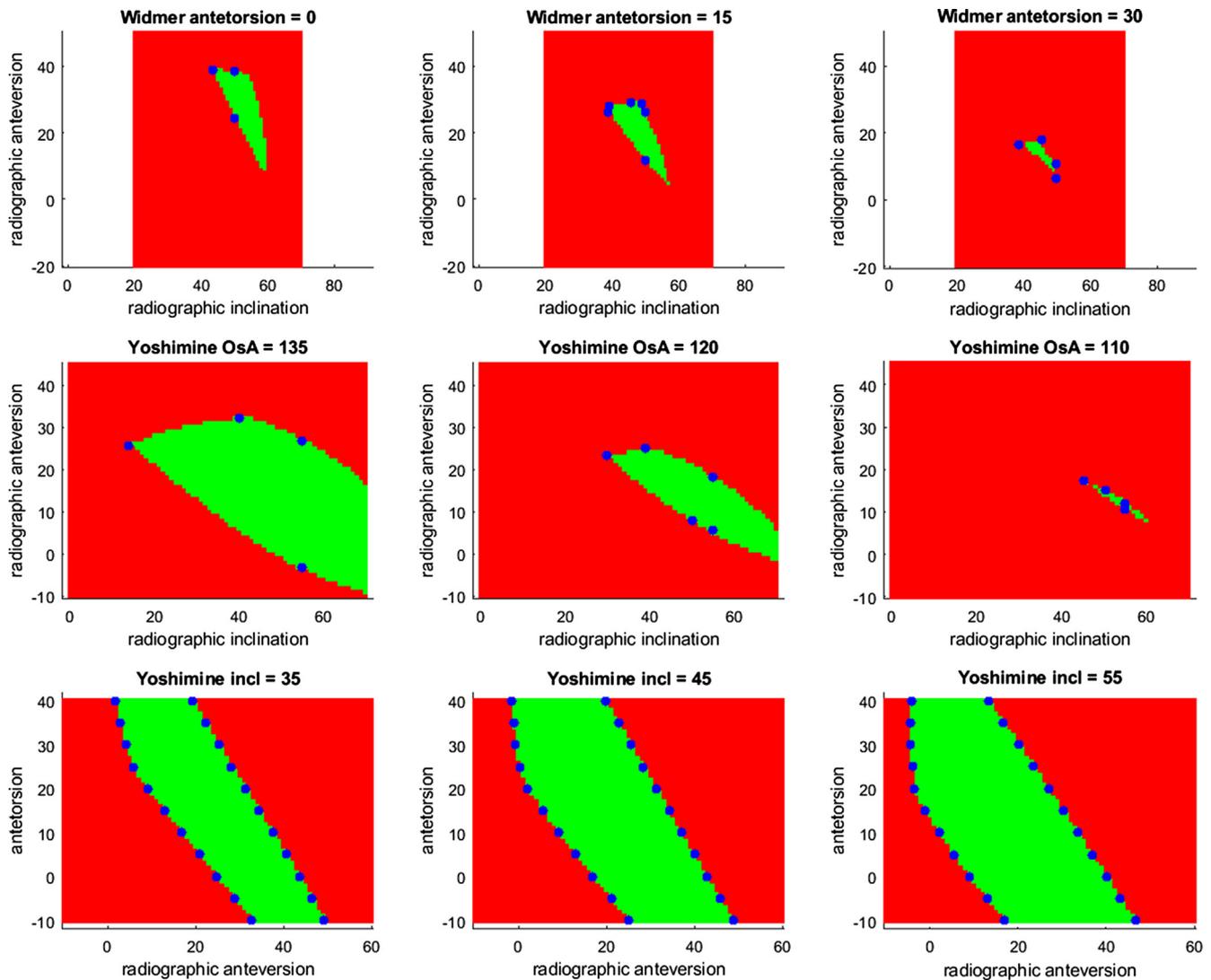
Fig. 4. Comparison of algorithm to results from literature. First row: comparison of the resulting target zone to results from Widmer and Zurfluh (2004). Points are extracted from the publication. The target zone by Widmer excludes cup inclinations greater than 50°. Therefore, only the target zone including inclinations smaller than 50° can be compared. Middle row: Comparison of resulting target zone to results from Yoshimine (2005). Last row: Comparison of resulting target zone to results from Yoshimine (2006).

target ROMs can be found but they are very different from each other. They can be given as maximum ranges for pure physiologic planes (Charbonnier et al., 2014; Johnston and Smidt, 1970; McCollum and Gray, 1990; Miki et al., 2007; Widmer and Zurfluh, 2004), combined motions (Barrack et al., 2001; Kapandji, 1985; Schuenke et al., 2010; Turley et al., 2011; Weber et al., 2016; Yoshimine, 2006) or motion sequences (Nadzadi et al., 2003).

Four exemplary ROM specifications (summarized in Table 2) were used as input for the algorithm presented. All other input parameters were set to the default values: antetorsion = 15°, neck-shaft angle = 130°, stem flexion = 3°, stem adduction = 5°, head radius 14 mm, neck radius 6 mm, cup opening angle = 180° and pelvic tilt = 0°. These default values were used throughout the sensitivity analysis if not specified otherwise. The resulting target zones were compared to each other qualitatively. For the following analysis, all four ROMs were applied.

2.2.2. Pelvic tilt

Different pelvic tilts ranging from −30° to +30° in 5° increments were applied. The remaining parameters were unchanged. Optimal

orientations were determined for each target zone. An orientation was declared as "optimal" if the minimal distance to prosthetic impingement is maximized:

$$\left(\phi_{\text{incl,opt}}, \phi_{\text{ant,opt}}\right) = \max_{(\phi_{\text{incl}},\phi_{\text{ant}})} d_{min}(\phi_{\text{incl}}, \phi_{\text{ant}}) \qquad (17)$$

The differences between the optimal orientations and those using the default parameters were calculated and compared. Linear regression was used to quantify the mean change of optimal inclination and anteversion depending on the pelvic tilt.

2.2.3. Initial neck orientation

The antetorsion was changed from −10° to 30° in 5° increments and the stem flexion and stem adduction was changed from 0° to 10° in 1° increments. This covers a range of different neck to femur orientations. The pelvic tilt was set to −15°, 0° and +15°. The differences between the "optimal" cup orientations and those using the default parameters were calculated and compared. Linear regression was used to quantify the mean change of inclination and anteversion depending on the stem orientations.
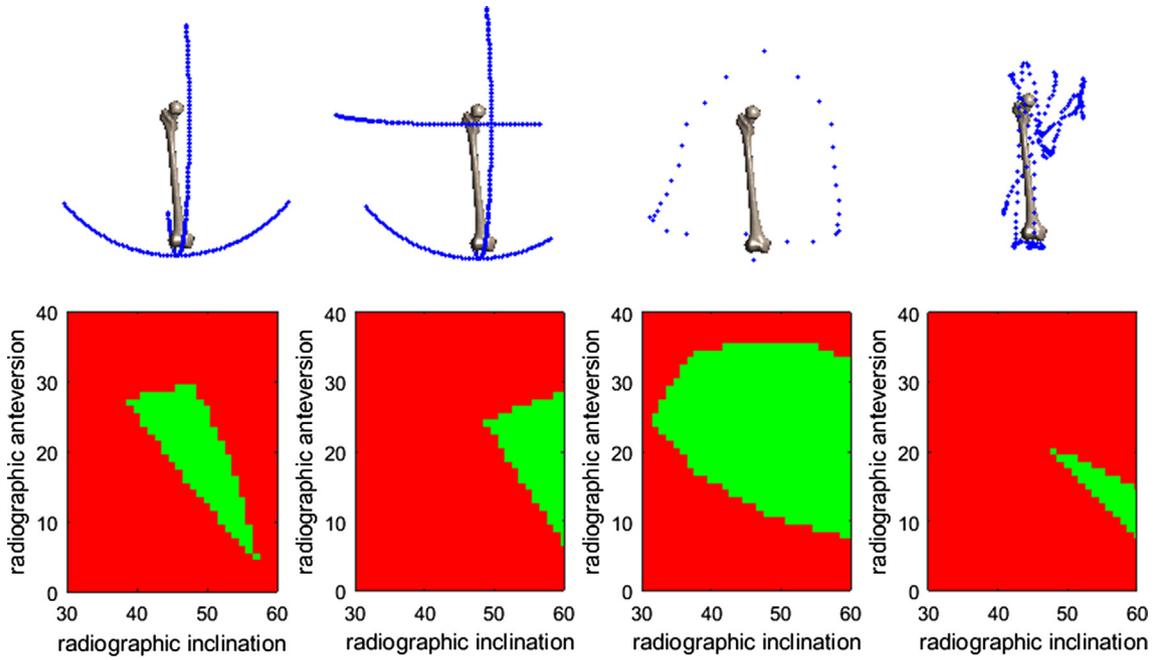
Fig. 5. Influence of the target ROM on resulting target zone for cup orientations.
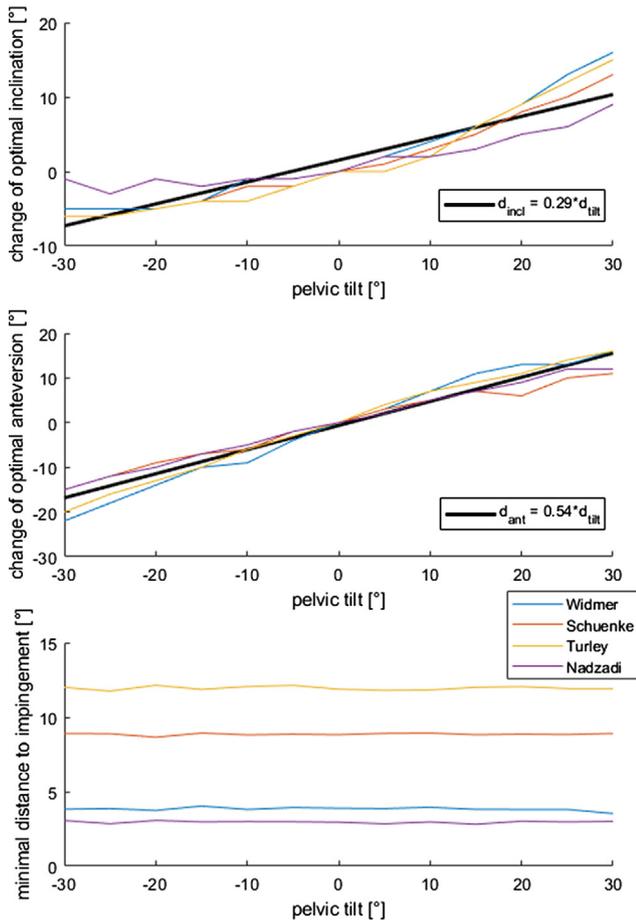

Fig. 6. Impact of pelvic tilt on resulting optimal implant orientation.

2.2.4. Technical ROM

The head radius was varied from 10 to 18 mm with an increment of 2 mm representing a sufficient range for the technical ROM. The differences between the "optimal" cup orientations

and those using the default parameters were calculated and compared.

3. Results

3.1. Comparison to literature

The resulting target zones using the same parameters as in literature with their reference values visualized as blue dots are shown in Fig. 4. The results match the results from literature. The computing time for 3621 cup orientations was less than two seconds.

3.2. Sensitivity analysis

Fig. 5 shows that the resulting target zones using different target ROMs are very different.

Fig. 6 shows the sensitivity of the optimal cup orientation on the pelvic tilt and their linear regression results. Furthermore, for each target ROM and pelvic tilt, the minimal distance to impingement is plotted. It indicates how much the cup orientation can be varied before impingement occurs. The distance to impingement values are quite large for the target ROMs resulting in a larger target zone (e.g. Turley) and vice versa. The distance to impingement is not dependent on the pelvic tilt.

Fig. 7 shows the sensitivity of the optimal cup orientation on the angular stem orientation. The distance to impingement is independent of the stem flexion but a change of antetorsion or stem adduction has an impact on the minimum distance to impingement and, therefore, on the size of the resulting target zone. When increasing stem adduction, the size of the target zone decreases. The size of the target zone increases with the antetorsion until it reaches a maximum and decreases afterwards.

The sensitivity of the optimal cup orientation with respect to a variation of the technical ROM is shown in Fig. 8. Both the "optimal" inclination and anteversion were constant for all technical ROMs tested. The minimum distance to impingement is negative for some for some target ROMs, meaning that no target zone could be identified. It can also be seen that with an increasing technical
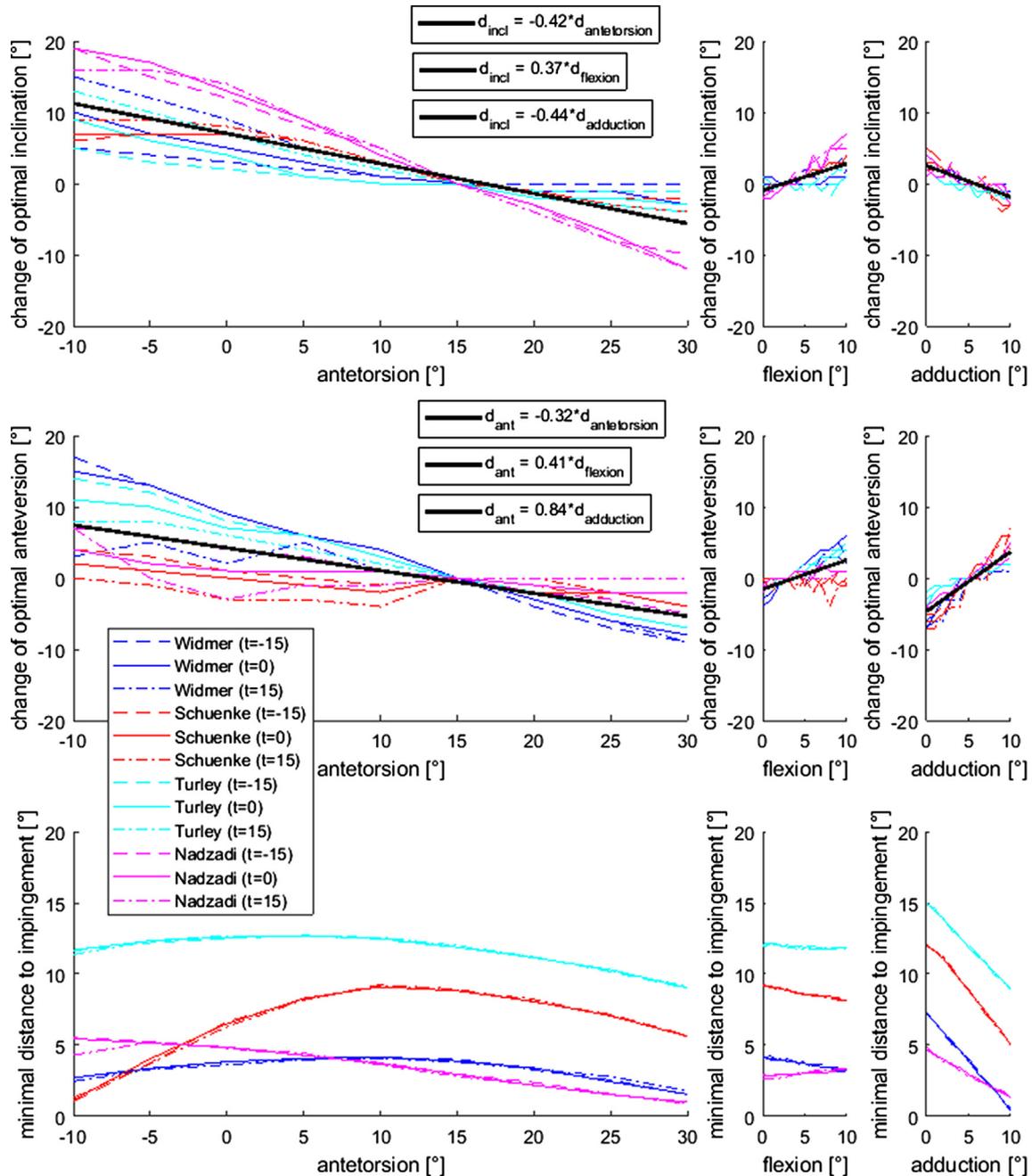
Fig. 7. Impact of stem orientation on resulting optimal implant orientation.

ROM, the distance to impingement is also increasing, i.e. the size of the target zone is increasing.

4. Discussion

A method for efficient ROM-based target zone calculation for THA is presented. The resulting target zones are consistent with the results from literature. The computation is simple and fast, as it is based on matrix multiplications and trigonometric formulas. Recalculating the target zone using different parameters, such as a changed stem orientation, can be performed on demand. The stem orientation might be different after insertion than originally planned or estimated before surgery. This method could be integrated into a navigation system to be used for intra-operative

adaptation of the cup target orientation for the actual stem alignment. Any arbitrary combined motion can be used as an input. The patient-specific pelvic orientation is also incorporated into the calculation.

The cup orientation was defined using the radiographic definition (Murray, 1993) relative to the pelvic coordinate system. The pelvic coordinate system can be defined by the APP, but also for example using the transverse pelvic plane (Dandachli et al., 2006) or by the definition recommended by the ISB (Wu et al., 2002). How the pelvic coordinate system is defined does not change this method. One only has to make sure that the same reference is used for defining the pelvic tilt and for aligning the cup intra-operatively.

Even though the method presented allows the consideration of any arbitrary motion, the question of which target ROM suits a
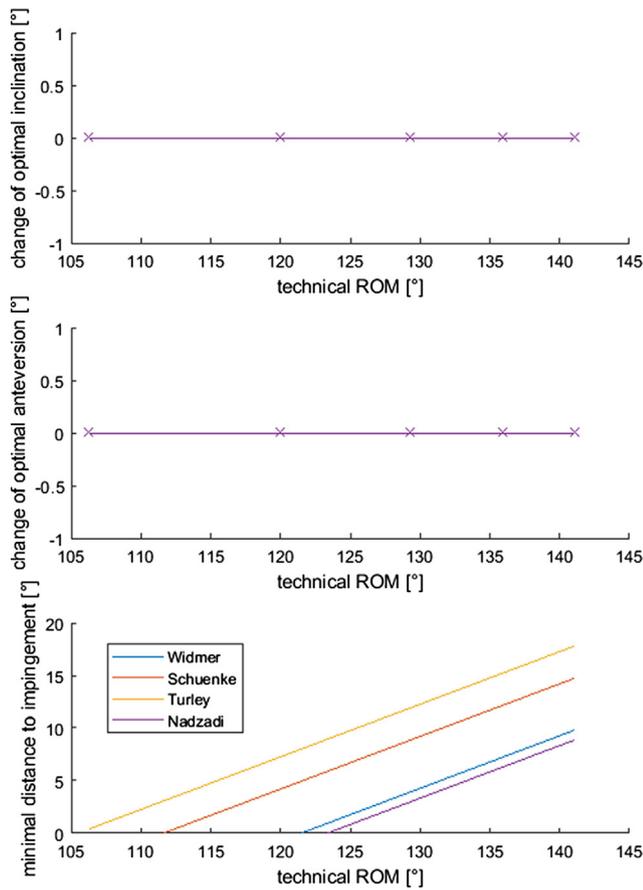
Fig. 8. Influence of the technical ROM on resulting optimal implant orientation.

pre-operative tilt measurement und planning has to be identified during operation and used for cup alignment. Whether the pre-operative pelvic tilt is suitable to use for hip planning remains unclear. While some studies suggest that the pelvic tilt is not influenced by THA (DiGioia et al., 2006; Murphy et al., 2013) other showed that it is changed (Ishida et al., 2011; Parratte et al., 2009). Also, the pelvic orientation is dependent on the lower spine (Buckland et al., 2015; Kanawade et al., 2014; Lazennec et al., 2004; Shah et al., 2017; Tamura et al., 2014). Due to different pelvic mobility, the change of pelvic tilt from standing to sitting (Kanawade et al., 2014) and in ready-to-rise positions (Shah et al., 2017) is patient-specific. Spine surgery might change the pelvic tilt and therefore the functional cup orientation. It is suggested to perform spine osteotomy prior to THA if both operations are needed (Zheng et al., 2014).

The combined anteversion is an accepted method for combined stem and cup alignment (Dorr et al., 2009; Ranawat and Maynard, 1991; Weber et al., 2016; Widmer and Zurfluh, 2004). The results of this current study show that not only the combined anteversion but the overall orientation including stem flexion and adduction should be considered. The impact of the stem flexion and adduction is as high as the antetorsion on the resulting target zone. The mean change of optimal inclination and anteversion relative to the increase of antetorsion is −0.42° and −0.32°. Dependencies found in literature are −0.77° for inclination and anteversion (Yoshimine, 2006) using the anatomical definition for anteversion, −0.7° for anteversion (Widmer and Zurfluh, 2004) and 0.33° for inclination and −0.35° for (Elkins et al., 2015) considering not only the ROM, but also a wear-related measure. It can be seen in the results in Fig. 7 that the variation of optimal cup orientations is quite high and depends on the pelvic tilt and the target ROM. The decrease of optimal anteversion relative to the antetorsion for the ROM defined by Widmer and Zurfluh is higher than the average. This explains why the formula derived by Widmer and Zurfluh has a greater absolute slope than in our study.

The dependencies found are, however, only an indicator for how much the ROM-based target zone is changed due to pelvic tilt differences or different stem alignments and that the technical ROM does not have an influence on the optimal cup orientation. It is not intended to be applied as a linear correction value. Although our algorithm provides an efficient method for patient-specific ROM-based target zone calculation which can be included in a computer-assisted THA planning and navigation systems, other criteria also need to be considered. The optimal cup orientation is not only dependent on the impingement-free ROM, but also on other factors, such as the bony coverage (Widmer, 2007), bony impingement (Kessler et al., 2008; Kurtz et al., 2010), resulting hip forces (Mellon et al., 2015; Pedersen et al., 2005; Pierrepont et al., 2016) and wear (Elkins et al., 2015). The number of parameters will rise when including these factors. Parameters which further need to be regarded which do not have an influence on prosthetic impingement but on patient-specific biomechanics and functional outcome include the center of rotation, offset, stem height, etc. Finding correction factors for each parameter is not feasible. They are also interdependent. Therefore, the overall optimal cup orientation has to be recalculated for each individual patient. The development of related methods for including all relevant criteria for patient-specific target zone estimation is part of our ongoing work.

Conflict of interest statement

specific patient has not yet been solved. The data from literature are not consistent and different target ROMs will result in a changed resulting target zone. The target ROM could be adjusted to the patient's age, activity level, flexibility and cultural-dependent postures. Rules of how a generic ROM can be adjusted to the patient-specific target ROM need to be defined.

The importance of integrating the pelvic tilt for optimal cup orientation is shown in the sensitivity analysis in this study and previous studies from literature (Babisch et al., 2008; Lazennec et al., 2017; Lembeck et al., 2005; Pierrepont et al., 2016). In the current study, a mean increase of "optimal" inclination by 0.29° and anteversion by 0.54° for every increase by 1° of pelvic tilt is measured. Lembeck et al. (Lembeck et al., 2005) found that for every decrease of pelvic tilt, the functional cup anteversion will increase by 0.7°. Babisch et al. (2008) found that "anteversion changes approximately 4° for every 5° of change in the pelvic tilt angle. Abduction [here: inclination] is less affected, changing approximately 1.5° for every 5° of change in the pelvic tilt angle.". This translates to a change of 0.3° for inclination and 0.8° for anteversion. The effect on the functional inclination coincides with our findings while the values for the change of anteversion are slightly larger. (Thelen et al., 2017) found that 1.88° increase of pelvic tilt leads to 1° decrease of functional anteversion. This translates to a correction factor 0.53° which coincide with our findings.

Different pelvic tilt acquisition techniques were proposed in literature including direct measurement on lateral X-rays (Eckman et al., 2006) during various activities (Pierrepont et al., 2016), or CT to weight bearing AP X-ray registration (Nishihara et al., 2003). Intra-operatively, the pelvic tilt does not have to be measured again. The same pelvic coordinate system as used for

in any respect. ConforMIS had no role in the study design, the collection, analysis and interpretation of data, in the writing of the manuscript or in the decision to submit the manuscript for publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2018.10.020.

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