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MRI-based registration of pelvic alignment affected by altered pelvic floor muscle characteristics

Petra Bendová [a,*], Pavel Růžička [b], Věra Peterová [c], Martina Fričová [b], Ingrid Špringrová [d]

[a] *Department of Anatomy and Biomechanics, Faculty of Physical Education and Sports, Charles University, José Martího, Prague 162 52, Czech Republic*
[b] *Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University, Prague, Czech Republic*
[c] *MRI Unit, Radiodiagnostic Clinic, 1st Faculty of Medicine and General University Hospital, Charles University, Prague, Czech Republic*
[d] *Department of Physiotherapy, Faculty of Physical Education and Sports, Charles University, Prague, Czech Republic*

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Abstract

Background. Pelvic floor muscles have potential to influence relative pelvic alignment. Side asymmetry in pelvic floor muscle tension is claimed to induce pelvic malalignment. However, its nature and amplitude are not clear. There is a need for non-invasive and reliable assessment method. An intervention experiment of unilateral pelvic floor muscle activation on healthy females was performed using image data for intra-subject comparison of normal and altered configuration of bony pelvis.

Methods. Sequent magnetic resonance imaging of 14 females in supine position was performed with 1.5 T static body coil in coronal orientation. The intervention, surface functional electrostimulation, was applied to activate pelvic floor muscles on the right side. Spatial coordinates of 23 pelvic landmarks were localized in each subject and registered by specially designed magnetic resonance image data processing tool (MPT2006), where individual error calculation; data registration, analysis and 3D visualization were interfaced.

Findings. The effect of intervention was large (Cohen's $d = 1.34$). We found significant differences in quantity ($P < 0.01$) and quality ($P = 0.02$) of normal and induced pelvic displacements. After pelvic floor muscle activation on the right side, pelvic structures shifted most frequently to the right side in ventro-caudal direction. The right femoral head, the right innominate and the coccyx showed the largest displacements.

Interpretation. The consequences arising from the capacity of pelvic floor muscles to displace pelvic bony structures are important to consider not only in management of malalignment syndrome but also in treatment of incontinence. The study has demonstrated benefits associated with processing of magnetic resonance image data within pelvic region with high localization and registration reliability.

Keywords: Pelvis; Magnetic resonance imaging; Image registration; Pelvic floor muscles; Malalignment; Sacroiliac joint; Electrostimulation; *in vivo*

1. Introduction

From a mechanical perspective, the pelvis is a closed linked structure. Motion of any link in the chain is dependent on motion of the other links. A primary function of the pelvis is to transfer loads generated by body weight and gravity during standing, walking and sitting (Snijders et al., 1993). Pelvis also represents a basis for the axial system, thus its alignment influences posture and stability of the spine.

At a balanced position, soft tissues of the pelvic system transmit external loads and keep the pelvic ring stable. When an extra load is applied onto the pelvic system, or the material properties of the soft tissues around the pelvic joints are altered, the relative positions of the pelvic bones change to adjust tension in ligaments and pressures in joint cartilage. If extra load exceeds the stabilizing capacity, the pelvic ring becomes unstable (Zheng et al., 1997). The tension in soft tissues becomes asymmetrical and regular load transfer through the lumbopelvic region is impaired. Failed

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[*] Corresponding author.
E-mail address: MPT2006@seznam.cz (P. Bendová).

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load transfer through the lumbopelvic region can manifest either as low back pain (Al-Eisa et al., 2006; Lee and Lee, 2004; Schamberger, 2002; Snijders et al., 1993) or as loss of urethra closure, causing stress urinary incontinence (Lee and Lee, 2004).

Bø and Sherburn (2005) defined function of pelvic floor muscles (PFM) as ability to perform a correct contraction, meaning a squeeze around pelvic openings and an inward movement of the pelvic floor. Recent studies showed that PFM also have potential to influence relative pelvic alignment and pelvic joint function via attachments to the bony pelvis. Pool-Goudzwaard et al. (2004) registered a significant counternutation of the sacrum when tension of PFM was simulated *in vitro*. Snijders et al. (1993) proposed that PFM can generate a direct compressive force on the sacroiliac joint (SIJ) and change the position of the joint. Unilateral increase of PFM tension, seen in patients suffering from levator ani syndrome, is claimed to generate force imbalance throughout the pelvic ring, resulting in displacement of pelvic bony structures (pelvic malalignment) (Malbohan et al., 1989; Schamberger, 2002; Tichý et al., 1999; Tichý, 2003). However, there is no reliable evidence regarding the nature and amplitude of such displacement.

Complex anatomy and spatial relationships within the pelvis have led researchers to use invasive techniques for precise assessment of pelvic kinematics. There is a need for a practical and non-invasive method that is accurate and reliable for pelvic alignment and motion measurements. Imaging techniques seem to be relevant for this purpose (Al-Eisa et al., 2006; Bussey et al., 2004; Buyruk et al., 1995; Lalonde et al., 2006; van Wingerden et al., 2004).

Magnetic resonance imaging (MRI), processing of the detected changes in atom nuclear magnetic moment after application of radiofrequency pulse (Westbrook and Kaut Roth, 2005), offers high resolution and multiplanar capabilities in addition to its non-invasive nature.

Concerning the pelvic region, only a few MRI-based studies have focused on the relationship between soft tissue characteristics and pelvic alignment. Handa et al. (2003) reported an association of certain pelvic phenotype with occurrence of pelvic floor disorders in a sample of 64 females. Hoyte et al. (2005) observed on 22 women racially predefined bony-soft tissue pelvic floor parameters, which, if increased, may incite the development of incontinence-related problems. Gutman et al. (2005) evaluated anatomical distances between the vaginal apex and the pelvic bony structures of 11 nulliparous women, concluding that there exists a consistent relationship between soft and solid structures of the pelvis.

In the present study, we focused on the role of PFM tension asymmetry in relative spatial pelvic organisation. The aim was to register the nature and amplitude of the pelvic displacements induced by unilaterally altered PFM characteristics using MRI data. In addition, we tested the reliability of registration procedure for intra-subject comparison of image data and its suitability for the pelvic region.

2. Methods

The study was designed as an experimental intervention trial based on comparison of normal and altered conditions in individual subjects (the control subjects became experimental subjects after the intervention).

The sample consisted of 14 adult nulliparous subjects, who were healthy volunteers recruited prospectively. Based on published data (Handa et al., 2003), the sample size was adequate to detect differences in pelvic alignment between the control and experimental group ($n = 12.1$; $\alpha = 0.05$; $\beta = 0.05$). Subject parameters were mean age of 26.5 and body mass index of 22.3. Exclusion criteria were a history of chronic low back pain, dysmenorrhoea, incontinence, gynaecologic operations and apparent musculoskeletal abnormalities in the pelvic region or the lower extremities. All subjects signed a letter of informed consent.

2.1. Intervention

A single-shot intervention of unilateral functional electrostimulation (FES) was applied onto right side of PFM to alter their characteristics. Based on findings of Kodešová et al. (2005), the idea of the intervention was to induce contemporary poststimulative shortening and increase of tension in PFM; mainly the coccygeus, the levator ani and the caudal portion of the gluteus maximus pars coccygeofemoralis (Tichý and Grim, 1985). The Institutional Research Ethics Committee of the Faculty of Physical Education and Sports at Charles University in Prague approved the experiment.

We used mid-frequency current with rectangular characteristics (Neuroton Universal 926; Medizintechnik AG, Rimbach, Germany); 50 Hz modulated frequency; 100–300 μs impulse latitude; 3 s impulses duration, 6 s pause; individually adopted overthreshold motoric intensity of 16–30 mA and 5 min duration. The surface punctual cathode was placed in the paracoccygeal region, vertical to the muscle course. The surface square anode was attached to the lower part of the gluteal muscles.

2.2. MRI management

Each subject underwent three MRI investigations. To identify intra-subject variance in MRI data without any alteration, we performed two sequent MRI examinations of controls. The subjects stood up from the gantry bench, stepped once on each leg and laid back. The third MRI scanning was performed immediately after the intervention.

MR imaging of the pelvic region was performed with 1.5 T static body coil (Gyroscan ACS-NT; Philips Medizin System, Hamburg, Germany) in coronal orientation (3D TFE gradient sequence; 1 mm slice thickness; 2 mm gap; 9.3–9.7 ms repetition time; 4.6 ms echo time; 256 × 256 matrix; 400 mm field of view; 11 min duration). Supine subjects were scanned with controlled uniform position of the lower extremities. The images were reviewed on Scanview workstation for data acquisition (version 2.0; a software product of 1st Faculty of Medicine, Charles University in Prague, Czech Republic).

The localization process, performed by two examiners, was based on interactive visual identification of the object at the bone/soft tissue boundary line. A set of identified objects (spatial coordinates) involved 23 strategic landmarks, which defined the sacrum, both innominates, the coccyx, both femoral heads and the L5 vertebra (Fig. 1a).

2.3. Registration process

The image orientation of the same subject taken at different time intervals differed irrespective to the standardized position or intervention. For intra-subject comparison of images, it was essential to superimpose two image sets of one subject onto each other by matching of the selected reference bodies (image registration) (Fitzpatrick et al., 2000) (Fig. 1c and d).

To facilitate effective processing of data registration and large data volume, we designed MRI data processing tool MPT2006 (software product of Czech Technical University in Prague, Czech Republic) (Fig. 2). An automated system of connected tables, formulas and service macro procedures was provided in MS Excel spreadsheet using add-in PopTools (version 2.69, Greg Hood – CSIRO, Canberra, Australia). Unigraphics (version NX 2; UGS PLM Software; Plano, Texas, USA) supplied spatial data reconstruction (Fig. 1b). The parameters of MPT2006 functions were accurately adjusted according to the registration requirements and conditions (e.g. each reference object was credited by a specific weight coefficient reflecting the localization demands). The basic outputs of MPT2006 are four magnitudes (Fig. 2):

- point shift distance (PSD), indicating the quantity of object displacement in space;
- point shift direction (PSDir), as definition of PSD in x–y–z, expressing the quality of object displacement in space;
- pelvimetry distance between two different objects, tracing relative positioning of pelvic structures; and
- spatial angle between planes representing the left innominate, the sacrum and the right innominate (pilot trial).

2.4. Statistical analysis

Inferential and comparative statistics were performed using StatistiXL (version 1.6; StatistiXL, Broadway-Nedlands, Australia). Parametrically distributed continuous data were compared by two-tailed paired Student's t-test for repeated measures. Statistical significance was assigned as $P < 0.05$. To allocate the amount of variation between groups, a multivariate model of variance analysis (ANOVA) for repeated measures was employed. We

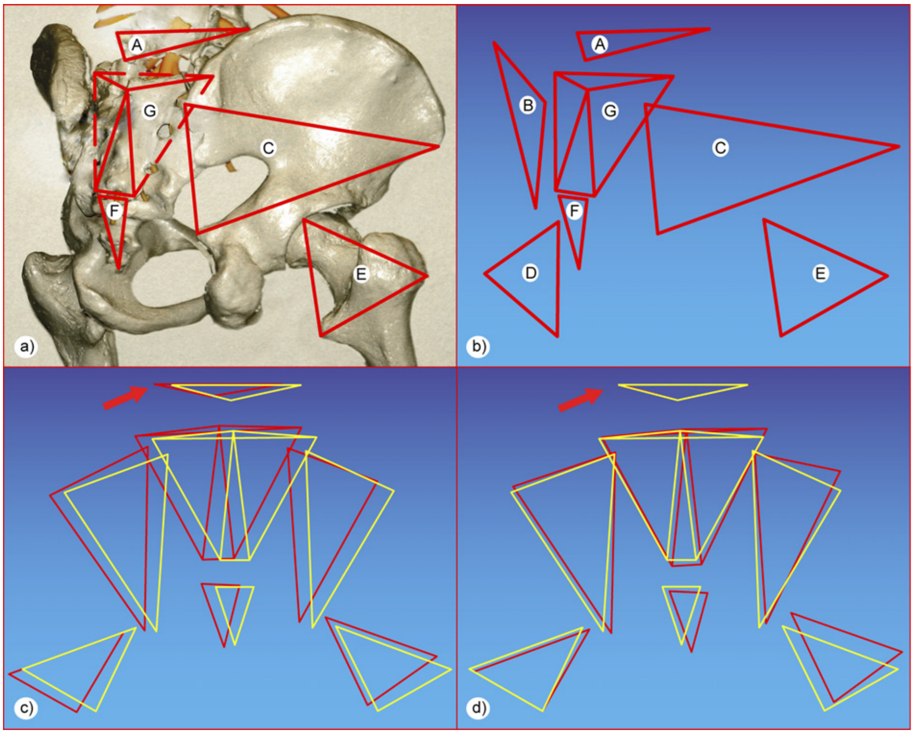

Fig. 1. 23 localized anatomical landmarks represent seven pelvic structures (a); A: vertebra L5; B, C: left, right innominate; D, E: left, right caput femoris; F: coccyx; G: sacrum. MRI data spatial visualization, wire model of the bony pelvis (b). Image registration (c,d) performed by matching of the L5 vertebra reference bodies (arrow) defined by three reference objects (processus spinosus, processus transversus on both sides). The situation before reposition (c), after reposition (d); the original view of the pelvis (solid line (yellow in web version)), the view of the pelvis in altered condition (dashed line (red in web version)).

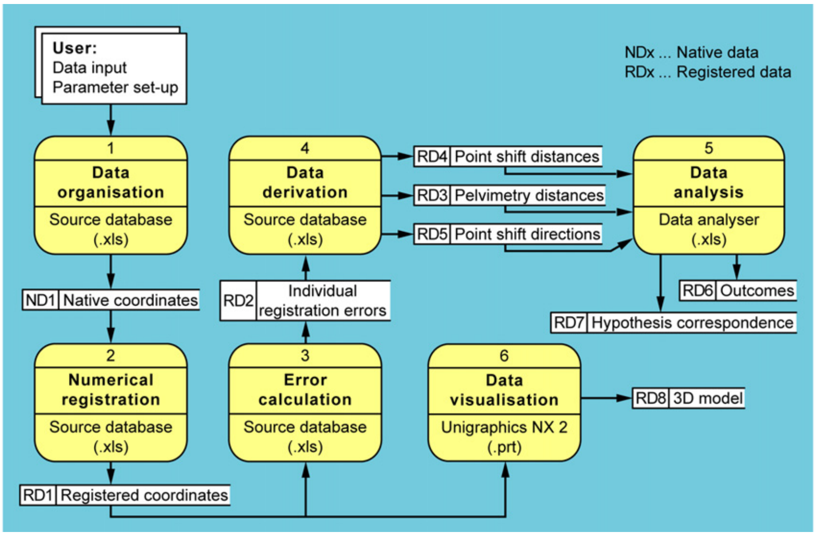

Fig. 2. MRI data processing tool MPT2006. Flow diagram of automatic function interface.

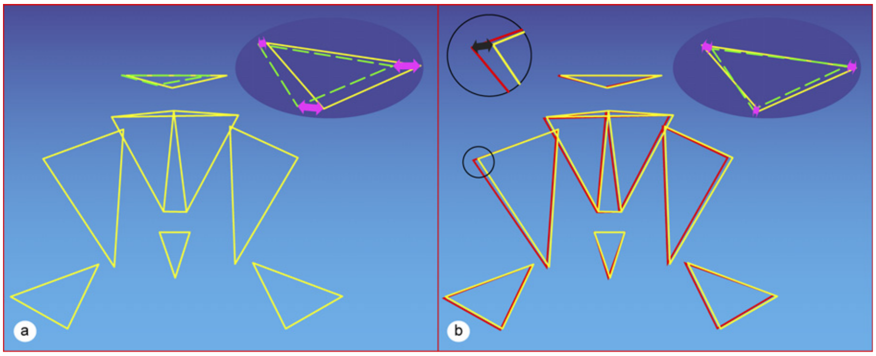

Fig. 3. Registration error determination based on existing matching inaccuracy of the corresponding reference bodies. Reposition of the original target objects into a position (b) indicated by the extent and the direction of residual distances (b, detail) after reference body matching (a). Individual registration error (in circle) = resulting spatial distance between the original target object (solid line (yellow in web version)) and the repositioned original target object (dashed line (red in web version)).

adopted Cohen's *d* to calculate the effect size of intervention.

2.5. Accuracy and reliability of employed registration method

The localization process was tested for acceptable intra-observer and interobserver reliability. Localization reliability of the same examiner at varying time intervals focused on two criteria, localizing the same object in different subjects ($n = 102$) and localizing different objects in the same subject ($n = 60$). We used spatial coordinates of 20 objects from two MRI exams of one subject to determine average localization error. Two examiners detected each object ten times. The mean of minimum–maximum intervals of x, y, z coordinates ($n = 240$) was taken as localization error value.

Prior to data processing, we performed testing of five registration modalities as combinations of factors affecting the accuracy and reliability of the registration process. The testing criterion focused on the modality that performed the best match of two MRI data sets of subject within the control group. The registration modality characterized by the L5 vertebra reference body and computational rigid-body point-based registration algorithm (Fitzpatrick et al., 2000) appeared to be the most accurate and therefore used in the data processing.

Registration error, virtual displacement of target objects originating in imprecise reference object localization, was allocated for each subject, each object and each direction individually (Fig. 3). The sum of localization and registration error was subtracted from the computed PSD. PSD was then considered as unbiased fair value (PSD value lower than total error was neglected).

3. Results

The ability of the examiner to localize the same object in different subjects[1] or to localize different objects in the same subject[2] demonstrated high level of reproducibility ($\text{IraCC}^1 = 0.9968$; $\text{IraCC}^2 = 0.9999$; $P < 0.01$). Localization agreement between two examiners was also high (IerCC = 0.9973; $P < 0.01$). The value of average localization error was 1.23 mm (SD 0.14). The analysis of object localization variability showed the medio-lateral direction to be the most difficult to localize. The cranio-caudal direction displayed the best localization characteristics (25–75% of 0–1 mm).

The effect of intervention was high, Cohen's $d = 1.34$. We found significantly larger quantity ($P < 0.01$; *t*-test) of object displacements in the experimental group, with intergroup mean difference of 1.43 mm (Table 1). The displacement of each individual object was however significantly different only in the case of trochanter major and minor on the right side. Results of controls revealed 2.5 mm displacements of pelvic structures as normal. Within the experimental group, the target objects shifted in space by 3.79 mm in average and more than 4 mm in 33% (9% in the control group). The right femoral head, the right innominate and coccyx showed the largest displacement. Displacement of right-sided objects, which occurred after the intervention on the right side, were significantly larger than displacement of left-sided objects ($P < 0.01$; *t*-test). We found no significant side divergence within the control group.

ANOVA test showed significant variation between groups in displacement direction quality ($P = 0.02$). The most frequent displacements in the control group were shifts in the right, posterior, inferior direction components. Objects in the experimental group shifted mostly in the right, anterior, inferior direction components; 45% of all objects shifted in spatial right-antero-inferior direction (RAI; Fig. 4; Table 1).

In detail, the most frequent character of object displacements indicated posterior rotation of the left innominate and medial tilting with posterior rotation of the right innominate. Counter-clockwise rotation in all three planes around the left oblique axis combined with lateral downslip was characteristic for sacral displacement. The coccyx was displaced to the right side in ventro-caudal direction.

Surprisingly, using ANOVA we observed no significant variation ($P = 0.78$) between groups in spectrum of 19 pelvimetry distances. The distance between apex coccyx and spina ischiadica on the right side, the course of the coccygeus muscle, shortened by a mean of 2.65 mm (2.5) in 79% of the cases after the intervention (max. 7.91 mm).

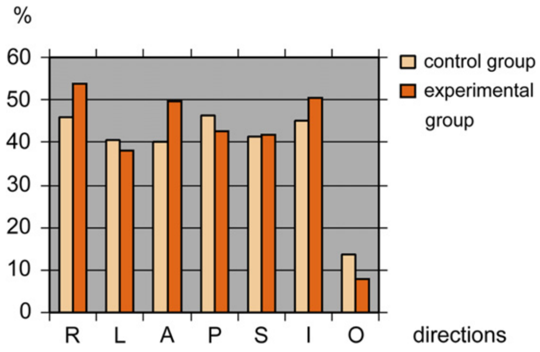

Fig. 4. Direction frequency of the object displacements. R: right, L: left, A: anterior, P: posterior, S: superior, I: inferior, O: no shift.

Table 1
Displacement (PSD) and displacement direction (PSDir) of the target objects

Object	Control group			Experimental group			Diff.	*P*-value
	Mean PSD	SD	PSDir	Mean PSD	SD	PSDir		
Apex coccyx	2.94	2.35	RPI	4.33	3.92	RAI	1.39	0.30
Basis coccyx sin	1.51	1.47	XPS	2.80	3.40	RAI	1.29	0.13
Basis coccyx dx	1.83	1.77	RAS	3.13	3.22	RAI	1.29	0.11
Cornu sacrale sin	1.97	1.62	XYZ	3.01	3.07	RAI	1.04	0.25
Cornu sacrale dx	1.70	1.74	RAS	3.28	3.58	RAI	1.59	0.11
Processus spinosus S1	1.95	3.03	LPI	1.71	1.41	RPI	−0.24	0.80
SIJ sin (pars craniodorsalis)	2.03	2.81	LPS	1.62	1.34	RPI	−0.41	0.59
SIJ dx (pars craniodorsalis)	1.01	1.28	XPS	1.99	1.55	LYS	0.98	0.09
ASIS sin	2.26	1.95	LPI	3.41	3.63	RPS	1.15	0.33
ASIS dx	2.04	2.64	LPI	4.07	3.42	LPS	2.04	0.07
PSIS sin	1.69	1.53	RAZ	2.45	1.43	RAI	0.76	0.13
PSIS dx	1.41	1.64	LAI	1.96	1.37	LYI	0.55	0.31
Spina ischiadica sin	2.03	1.92	RPI	2.96	3.25	RAI	0.92	0.35
Spina ischiadica dx	2.58	2.02	LPS	3.96	3.36	RYI	1.38	0.23
Trochanter minor sin	3.83	2.92	RPI	5.67	4.15	RAI	1.84	0.12
Trochanter minor dx	3.03	2.62	RPI	6.75	5.92	RAS	3.72	0.01*
Trochanter major sin	4.02	4.41	XYI	4.79	3.01	RAI	0.77	0.58
Trochanter major dx	3.95	2.28	RYS	9.07	8.45	XYS	5.12	0.05*
Fovea capitis femoris sin	2.92	2.25	LPI	3.86	3.20	RPI	0.94	0.42
Fovea capitis femoris dx	2.40	2.30	RPS	4.90	4.19	RAS	2.50	0.08
Total ($n = 280$)	2.36	2.4	RPI	3.79	4.01	RAI	1.43	0.00*

PSD in mm. PSDir: spatial shift of the target object in the direction code; R: right, L: left, A: anterior, P: posterior, S: superior, I: inferior, XYZ: same shift frequency in both directions along relevant axis. Diff.: mean experimental PSD – mean control PSD difference. Dx: right; sin: left.

* Two-tailed paired Student's *t*-test significant at $P < 0.05$.

However, the distance shortened by a mean of 2.44 mm (2.02) in 71% of the control cases as well. Analysis of the other distances between PFM attachments revealed a difference in average baseline and altered distance between cornu sacrale and trochanter major on the right side (the course of the coccygeofemoralis muscle) ($P = 0.07$; *t*-test). After intervention, the distance shortened by 2.28 mm in average (4.43) with a maximum of 11.08 mm (by mean of 0.73 mm (2.14) in controls).

4. Discussion

The study involved registration of normal pelvic configuration and altered pelvic alignment associated with unilateral PFM activation *in vivo*. We demonstrated significant variation in quantity and quality of normal and induced relative pelvic displacements (Table 1) using a specially designed processing tool (Fig. 2). In the experimental group, the right femoral head, the right innominate and the coccyx showed the largest displacement. The findings support the conclusions of Pool-Goudzwaard et al. (2004) and Snijders et al. (1993) that pelvic floor muscles influence relative alignment of all pelvic bony structures.

Possible consequences of pelvic malalignment are important to consider. O'Sullivan et al. (2002) reported altered motor control of PFM in patients suffering from impaired SIJ mobility and pain. Bendová et al. (2004) demonstrated change in load distribution detected under the feet when PFM were unilaterally activated. In addition, persisting changes in local pelvic dispositions of solid structures may predispose to incontinence-related problems, as indicated by Handa et al. (2003) and Lee and Lee (2004).

The observed nature of altered pelvic alignment is consistent with the pelvic malalignment described by Tichý et al. (1999) regarding backward sacral torsion around the left oblique axis. However, it differs from Schamberger's pelvic malalignment theory (2002), characterized by forward sacral torsion around the left oblique axis. The observed component of posterior sacral rotation corresponds to the sacral counternutation produced by *in vitro* simulated tension in PFM, as reported by Pool-Goudzwaard et al. (2004). Surprisingly, we found posterior rotation in both innominates. This is in contrast to the common idea of persisting innominate shear, considered the main pelvic malalignment symptom (Greenman, 1986; Hungerford et al., 2004; Schamberger, 2002; Tichý, 2003). The right innominate posterior rotation points more to an approximative effect of the activated PFM, as hypothesized by Snijders et al. (1993). We detected a ventral component in the coccyx displacement after unilateral PFM activation, which is identical to findings of Bø et al. (2001).

Kodešová et al. (2005) objectified the employed intervention approach by ultrasonography measures of PFM parameters. Our results report high intervention effect and point to the lower part of the gluteus maximus as the muscle predominantly affected by the intervention. However, there are individual factors (applied intensity, tissue permeability, sensitivity to current diffusion or baseline soft tissue proportions), which biased intervention uniformity, resulting in relatively high inter-subject displacement variability (Table 1).

Handa et al. (2003) found significant difference in six out of twelve distances, measured between pelvic bony structures from 2D MR images, in subjects with pelvic floor disorders compared to the controls. We did not find significant intergroup difference in any of 19 pelvimetry distances, although the shifts of related objects were obvious. We see the benefits in comparing planar projections of the distances, because the distance value does not have to reflect the character of spatial shift of related objects distinctively.

We performed a pilot trial of spatial angle computation between the main pelvic elements relative to each other. The angular ranges of innominate angular motion were similar to Bussey et al.'s (2004) and Sturesson et al.'s (2000) measures. Although the pilot findings were not sufficiently demonstrative, we see large potential in closer observation of angular relationships in related pelvic structures.

We consider high localization reproducibility of MRI data ($P < 0.01$) and highly accurate process of registration provided by MPT2006 as an important output of the present study. West et al. (1997) proposed registration error lower than 1 mm as high registration accuracy. Fitzpatrick et al. (1998) assessed registration error based on estimation of localization inaccuracy within the reference bodies. In our study, we applied error calculation based on existing matching inaccuracy of reference bodies, producing registration error for each target object individually, 0.57 mm (0.37) in average (Fig. 3).

The registration process seemed sensitive to factors such as reference body disposition towards reference system orientation or towards other pelvic structures; behaviour of the reference body within the chain of pelvic structures; the number and localization quality of the reference objects, etc. The vertically oriented body of sacrum did not verify as an optimal reference body, due to large ventro-dorsal registration deviations and high level of position dependency on both innominates. The horizontally oriented and relatively independent L5 vertebra produced minimal registration errors and proved to be optimal as the reference body for image registration within the pelvic region (Fig. 1c and d).

The supine position in the gantry bench represents a limitation of our study. Although Fielding et al. (1996) observed no significant difference in female PFM characteristics during supine or upright position, Bø and Finckenhagen (2003) and Frawley et al. (2006) found changes in vaginal resting pressure depending on body position. The upright imaging in an open-configuration MRI unit (Bertschinger et al., 2002) or the combination of imaging techniques (Bussey et al., 2004; Lalonde et al., 2006) could be a solution.

The implications of the present study extend beyond the improved understanding of the pelvic alignment related to PFM function. The research of other different load impacts affecting pelvic stability should be supported.

5. Conclusions

Using MRI data, the present study demonstrated that simulated tension asymmetry of PFM affects the relative positioning of pelvic bony structures and causes pelvic malalignment. The amplitude of induced displacements was significantly different from the control sample. The observed nature of induced displacements did not identify in total with any of recent hypotheses. However, there are partial conformities, such as downslip of the sacrum combined with counter-clockwise spatial rotation around the left oblique axis.

The consequences arising from the capacity of PFM to displace pelvic bony structures are important to consider not only in management of pelvic malalignment syndrome but also in the treatment of incontinence-related problems.

This study has demonstrated benefits associated with processing of MRI data in terms of high localization and registration reliability. The convenience of the designed MRI data processing tool (MPT2006) is direct data registration, analysis, automatic spatial visualization, error calculation and outcome comparison with predefined parameters. The ability to adjust MPT2006 settings makes it universal in processing of any image data and may favour its application in clinical practice.

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