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Analysis of sacro-iliac joint screw fixation: does quality of reduction and screw orientation influence joint stability? A biomechanical study

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Abstract

Introduction Treatment of posterior pelvic ring injuries is frequently associated with pain or/and high mortality rates. Percutaneous sacro-iliac (SI) screw fixation has proved to be one of the methods of choice, providing minimal operative time, blood loss and wound-related morbidity. However, fixation failures due to secondary fracture dislocation or screw backing out have been reported. There is a little knowledge regarding the impact of varying screw orientation and quality of reduction on the fixation strength.

Purpose The purpose of the present study was biomechanical investigation of joint stability after SI screw fixation and its dependence on quality of reduction and screw orientation.

Methods Thirty-two artificial hemi-pelvices were assigned to four study groups and simulated SI dislocations were fixed with two SI screws in oblique or transverse screw orientation and anatomical or non-anatomical reduction in group A (oblique/anatomical), B (transverse/anatomical), C (oblique/non-anatomical) and D (transverse/non-anatomical). Mechanical testing was performed under progressively increasing cyclic axial loading until fixation failure. SI joint movements were captured via optical motion tracking.

Fixation performance was statistically evaluated at a level of significance $p=0.05$.

Results The highest cycles to failure were observed in group A (14038±1057), followed by B (13909±1217), D (6936± 1654) and C (6706±1295). Groups A and B revealed significantly longer endurance than C and D ($p\leq0.01$).

Conclusions Different screw orientations in the presented model do not influence substantially SI joint stability. However, anatomical reduction is not only mandatory to restore a malalignment, but also to increase the SI screw fixation strength and prevent fixation failures.

Keywords Posterior pelvic ring injuries · Sacro-iliac screw fixation · Hemi-pelvis · Sawbones · Joint stability

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Introduction

Posterior pelvic ring injuries are common in high-energy polytrauma patients. They could lead to disability and chronic pain if reduction and fixation are not properly performed [1]. Anatomic reduction and rigid internal fixation are the goals of the definitive operative treatment [2]. Open reduction and internal fixation of the posterior pelvic ring with a combination of an SI screw and plates have been proved to provide increased stability compared to the use of one of these fixation devices alone [3, 4]. However, it may be associated with substantial intra-operative blood loss, infection rates between 6 and 25 %, and wound-related complications of up to 25 % [5]. Therefore, closed reduction and percutaneous insertion of two screws may be an alternative approach, resulting in higher loads to failure in comparison to the use of a single screw [6, 7], and associated with less operative time, minimal blood loss, and low wound-related morbidity [5]. The standard

technique of percutaneous screw fixation in vertical unstable SI dislocations is placing screws through the SI joint perpendicularly to its articular surfaces with posterior to anterior and inferior to superior orientation (oblique screw path), or perpendicularly to the fracture line in cases of vertical sacral fractures (transverse screw path) [8]. The alignment of the oblique screw trajectory within the main axis of the S1 corridor can be difficult and may require navigation techniques and prolonged surgical time [9]. Transverse SI screw placing parallel to the coronal and transversal planes is from a radiological point of view easier to achieve, but associated with a reduced S1 osseous corridor diameter [10]. To our knowledge, there are no existing studies that examine the stability of two SI screws on the level of S1 with different screw orientations in an anatomically reduced versus a non-anatomically reduced SI joint dislocation model.

Hence, the objective of the present study was (1) to investigate the stability of fixation in a dislocated SI joint model comparing the standard technique with two screws inserted perpendicularly to the SI joint versus an alternative technique with two screws inserted parallel to the coronal and transversal plane and (2) to compare these configurations after an anatomical and non-anatomical SI joint reduction. We hypothesized that screws inserted in different orientations do not considerably alter the stability, and that non-anatomical reduction of the SI joint leads to substantially lower stability.

Materials and methods

Specimens and instrumentation

Thirty-two fourth generation composite hemi-pelves and sacrum specimens (*#3405 Hemi Pelvis*, *#3405-2 Sacrum*, Sawbones, Vashon Island, WA, USA) were used in this study. SI joint dislocation was provided by the absence of any initial linkage between the hemi-pelvis and sacrum. For fixation of the SI joint two 80-mm long partially threaded 7.3-mm titanium cannulated screws with washers (DePuy Synthes, Zuchwil, Switzerland) were used.

Two fixation criteria were defined as follows:

1) Quality of SI joint reduction. Either an anatomical or a non-anatomical reduction was performed. The former was conducted by re-aligning the articular SI surfaces to their predetermined congruent joint position. Vertical and horizontal displacement of the ilium 10 mm superiorly and posteriorly relative to the sacrum with respect to the anatomically reduced case simulated the latter.
2) Screw orientation. Two screws were placed either in an oblique or a transverse position. In case of the former, they were oriented perpendicularly to the SI joint in 25°

inferior to superior angle in the coronal plane and in 25° posterior to anterior angle in the transverse plane, according to the safe zone [10, 11]. For the transverse position, the screws were inserted in 0° angle respective to both the coronal and transversal planes. Each screw was tightened after placement with 3 Nm using a dynamometric screwdriver.

The combination of both options resulted in four study groups with eight specimens each, instrumented in four different SI joint screw fixation fashions as follows: group A—anatomical reduction and oblique screw orientation (Fig. 1a-b); group B—anatomical reduction and transverse screw orientation (Fig. 1c-d); group C—non-anatomical reduction and oblique screw orientation (Fig. 1e-f); group D—non-anatomical reduction and transverse screw orientation (Fig. 1g-h). Each specimen was instrumented under fluoroscopic guidance by an experienced surgeon (GW).
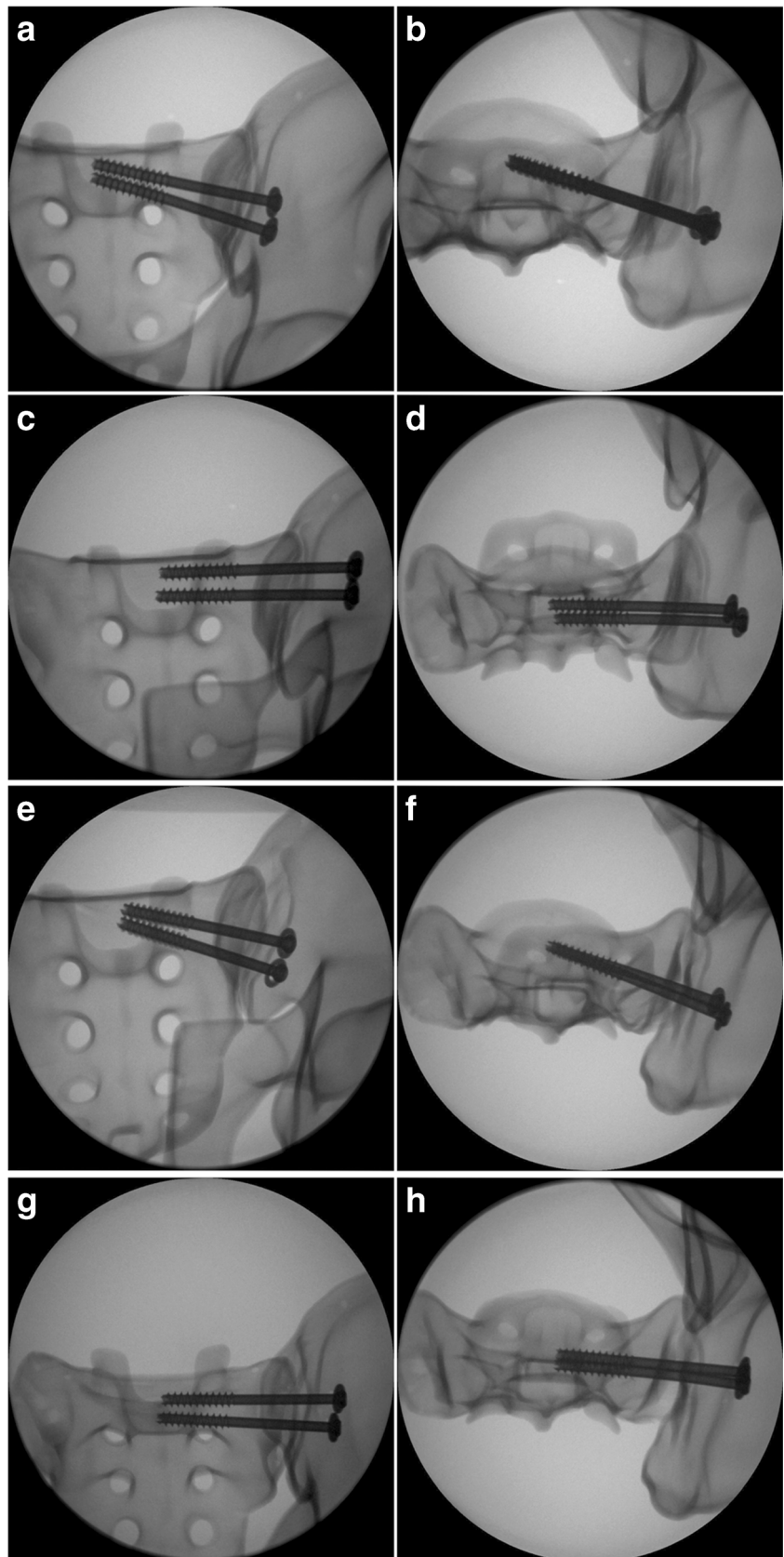
Inverse-dynamic gait analysis

An inverse-dynamic analysis of normal gait was performed using AnyBody Modeling System™ (v. 5.0, AnyBody Technology A/S, Aalborg, Denmark) to assess the most physiological relation between axial load and lateral bending moment acting in the SI joint. Under an assumed body weight of 723 N, the peak moment acting around the medio-lateral axis was found to be 30 Nm, as shown in Fig. 2.

Setup for mechanical testing

Mechanical testing was performed on a servohydraulic test system (Bionix 858.20; MTS Systems, Eden Prairie, MN, USA) equipped with a 4 kN/100 Nm load cell. The setup with a specimen mounted for testing is shown in Fig. 3. Each specimen was aligned and tested in an upright standing position. Compression loading along the machine axis was applied to the sacrum with 41-mm anterior offset relative to the posterior-superior S1 endplate aspect, generating at the same time the required moment around the medio-lateral axis as calculated from the inverse-dynamic gait analysis. For that purpose a custom steel plate with an L-profile was used. The sacrum was fixed to the vertically oriented side of the plate via two screws inserted through the fourth sacral foramen. The horizontal part of the plate was attached to the machine actuator via a double cardan joint. The iliac bone was supported on the machine base in a polymethylmethacrylate platform, fixed with one screw through the acetabulum. Two retro-reflective marker sets were attached to the iliac crest and the sacrum for optical motion tracking.

Fig. 1 X-rays of the SI joint fixation in the study groups (**a**) group A, anteroposterior view; (**b**) group A, inlet view; (**c**) group B, anteroposterior view; (**d**) group B, inlet view; (**e**) group C, anteroposterior view; (**f**) group C, inlet view; (**g**) group D, anteroposterior view; (**h**) group D, inlet view
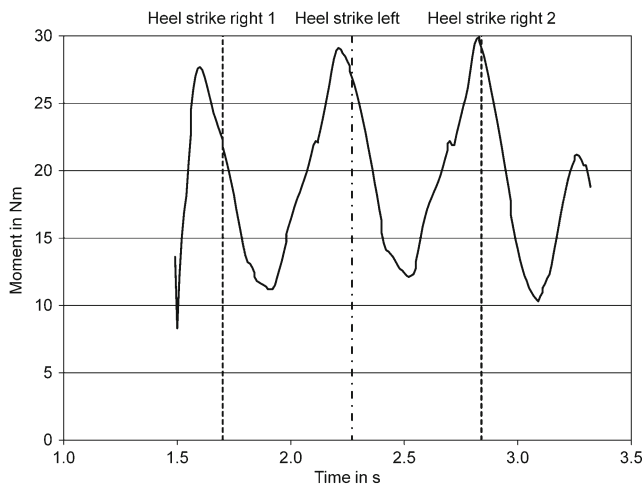
Fig. 2 Output of the inverse-dynamic gait analysis showing the moment acting around the medio-lateral axis in the SI joint during normal gait

Loading protocol

Progressively increasing cyclic loading in axial compression with a physiological profile of each cycle was applied at a rate of 3 Hz [12]. Keeping the valley load at a constant level of 50 N, the peak load, starting at 200 N, was constantly increased (cycle by cycle) at a rate of 0.04 N/cycle until catastrophic failure of the specimen. The application of progressively increasing cyclic loading aims to achieve construct failure within a predefined number of cycles and has been found useful in previous studies [13, 14].

Data acquisition and evaluation

Machine data in terms of axial displacement (mm) and axial load (N) were acquired from the machine actuator and the load cell at a rate of 128 Hz. Based on these, axial stiffness (N/mm)

Fig. 3 Test setup showing a specimen mounted for mechanical testing in anterior (*left*) and lateral (*right*) view. *Vertical arrows* denote loading direction

was calculated from the linear slope of the load–displacement curve of each specimen at test start (Initial Stiffness), and then after 1000 cycles (stiffness 1 k), 2500 cycles (stiffness 2.5 k), and 5000 cycles (stiffness 5 k).

Relative SI joint movements were investigated by means of three-dimensional optical motion tracking using five Pro Reflex MCU cameras (Qualisys AB, Gothenburg, Sweden). Optical motion tracking data were continuously recorded at a rate of 100 Hz. Based on these, relative displacements (mm) of the most superior and inferior aspects of the SI joint as well as relative SI joint flexion movements (deg) were calculated throughout the mechanical tests. The following different criteria for construct failure were defined: non-linear deviation in the relative SI flexion movements over time, and 2 mm relative displacements of the most superior and most inferior aspects of the SI joint. The numbers of cycles until fulfilment of each of these failure criteria were calculated, resulting in the parameters of interest 'nonlinear deviation', '2-mm translation superior' and '2-mm translation inferior'.

Another parameter of interest, 'cycles to failure', was defined as the minimum number of cycles when any of the failure criteria was fulfilled for the respective specimen.

Statistical evaluation was performed using the IBM SPSS software package (v.21, IBM SPSS, Armonk, NY, USA). Descriptive statistics was performed to calculate the mean and the standard error of the mean (SE) for each parameter of interest in each study group. Normal distribution was checked with the Shapiro-Wilk test. Paired-samples T test was carried out to detect significant differences between the paired groups A and B, respectively, C and D. One-way ANOVA with Bonferroni post hoc tests were conducted to screen statistical differences between the other possible pairs of groups. Level of significance was set to 0.05 for all statistical tests.
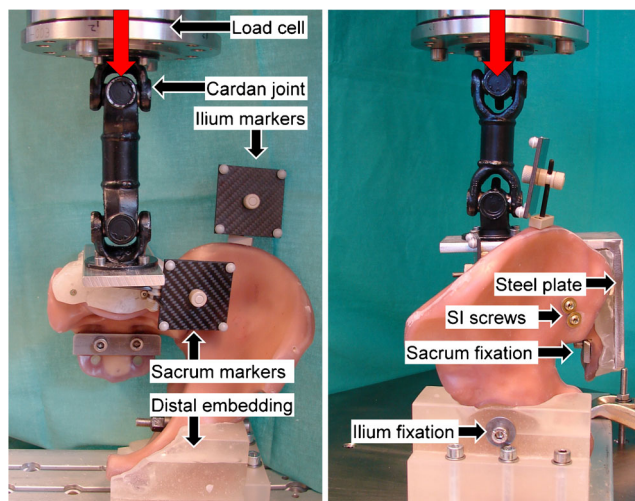
Results

All parameters of interest were normally distributed.

Results for axial stiffness in each of the predefined time points are summarized in Fig. 4. The highest values for initial stiffness (N/mm) were observed in group A (177.4±11.8, mean ± standard error of mean), followed by group B (173.2±11.2), group C (106.8±15.7) and group D (103.3±12.3). The values in groups A and B, compared to groups C and D were thereby significantly higher ($p < 0.01$). Stiffness 1 k (N/mm) was with the highest values in group B (184.7±10.0), followed by group A (180.9±17.6), group C (102.3±13.8) and group D (97.3±12.8). The values in groups A and B were significantly higher than those in groups C and D ($p \leq 0.01$). In view of stiffness 2.5 k (N/mm), group B was again with the highest values (184.0± 10.1), followed by group A (174.1±17.3), group C (96.1±12.4) and group D (92.5±12.0). These values were significantly
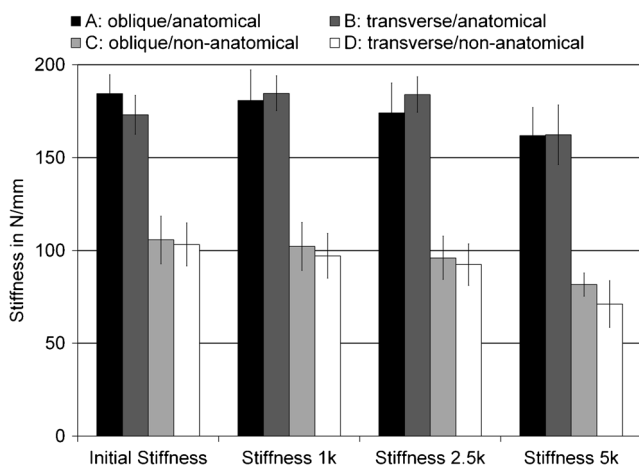
Fig. 4 Diagram representing the parameters of interest 'initial stiffness', 'stiffness 1 k', 'stiffness 2.5 k' and 'stiffness 5 k' in the study groups in terms of mean values and standard error of mean

higher in groups A and B in comparison to groups C and D ($p \leq$ 0.01). The same tendency was observed for stiffness 5 k (N/mm), with group B revealing the highest values (162.4± 17.2), followed by group A (161.9±16.4), group C (81.7±6.7) and group D (71.1±13.5). Groups A and B revealed again significantly higher values than groups C and D ($p \leq 0.01$).

The results with regard to fulfilment of the different failure criteria are summarized in Fig. 5. In view of the parameter of interest 'nonlinear deviation' group B showed the highest endurance, reaching the respective criterion (non-linear deviation in the relative SI flexion movements curve over time) after 16750±1272 cycles, followed by group A (14784±748), group D (10762±3074) and group C (7119± 1460). The corresponding differences were significant for groups A and B compared to group C ($p \leq 0.01$). Group A was with the highest number of cycles regarding '2-mm translation superior' (14654±1020), followed by group B (14159± 1087), group D (8165±1885) and group C (7519±1283). Significantly higher values were observed in groups A and B compared to group C ($p \leq 0.01$), and tendency towards
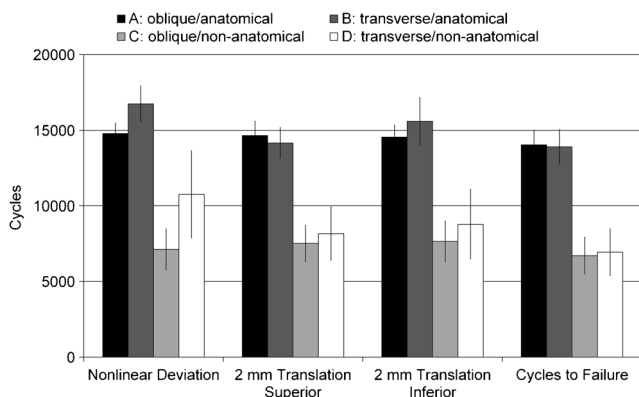
significance was observed in the former two groups compared to group D ($p=0.05$ and $p=0.08$, respectively). Group B revealed the highest number of cycles regarding '2-mm translation inferior' (15598±1676), followed by group A (14551± 848), group D (8784±2442) and group C (7653±1435). Significant differences were observed between groups B and C ($p=0.02$). Finally, the highest 'cycles to failure' were observed in group A (14038±1057), followed by group B (13909±1217), group D (6936±1654) and group C (6706± 1295), with significantly higher values in groups A and B compared to groups C and D ($p \leq 0.01$).

Discussion

The aim of the present study was to investigate dependence of fixation stability in a dislocated SI joint model on quality of reduction and SI screw orientations.

From a biomechanical point of view, the best SI joint or fracture reduction and interfragmentary compression could be achieved with a screw orientation perpendicular to the SI joint or the fracture line, preferring an oblique screw position for SI joint dislocations and a transverse position for sacral fractures. However, one main finding in our study showed similar stability for either of the two screw orientations to fix SI disruption.

The clinical decision for SI screw insertions in an oblique or transverse orientation is primarily based on the injury pattern in the posterior pelvic ring and the prevalence of sacral dysmorphism [10, 15–18]. Whereas SI disruptions and lateral sacral fractures (type I+II according to Denis classification [19]) can be addressed by both screw orientations, central sacral fractures (type III according to the same classification) can only be fixed with a transverse screw position. In contrast, in sacral dysmorphism no osseous corridor for a transverse screw orientation on the level of the first vertebra exists. According to the vestibule concept of Carlson, the largest osseous corridor exists perpendicular to the plane with the smallest pedicle diameter, whereas pathing such region non-perpendicularly in a transverse orientation will reduce the osseous corridor diameter and therefore increase the risk for screw misplacement [10]. On the other hand, a transverse SI screw orientation facilitates the use of longer trans-sacral screws up to the contralateral SI joint to increase the fixation strength due to a longer screw tip anchorage in the sacrum or even up to the contralateral ilium in bilateral fractures or as salvage procedures after failed standard screw fixation [15, 17].

The second main finding in our study was that non-anatomical reduction reduces significantly the overall construct performance compared to the anatomically reduced cases. Non-anatomical reduction can lead to nonunion,

Fig. 5 Cycles until fulfilment of the four different failure criteria in the study groups in terms of mean values and standard error of mean

malalignment, limb length discrepancy and disabling chronic pain. Mullis et al. showed that anatomical reduction followed by percutaneous fixation was a good predictor of favourable clinical results after 1-year follow-up [20]. Similar results were observed by Dujardin who found poor clinical results when the SI joint was not properly reduced in pure SI joint dislocations [21]. Mc Laren et al. also found better functional scoring and less pain when residual displacement was less than 1 cm [22]. In contrast, other clinical studies showed no effect of residual displacements in posterior ring injuries on functional outcomes [23]. However, our results showed poor stability when non-anatomical reduction is performed, caused by a decreased contact area of the articular surfaces. Especially the SI joint, being an amphiarthrosis, is characterized by heterogeneous shaped articular surfaces with partial interdigitation, which increases the intrinsic stability of the joint. Malreduction will result in joint-incongruence with loss of such osseous stabilization.

Based on this, anatomical reduction is not only advised in order to restore the malalignment, but also to achieve maximal stability.

There are some limitations to be disclosed in the present study. One of them was the use of an artificial instead of a cadaveric model, implicating less physiological conditions. However, the availability of cadavers usually limits the sample size in biomechanical experiments, and the number of samples used in published work is generally small [9]. In addition, composite test materials resemble more homogeneous specimens' properties, especially focusing on heterogeneous shaped SI joints, resulting in less data variations and therefore in higher test reliability [24]. Another limitation was the use of a hemi-pelvis set-up, which makes the model appear less physiologically complete in comparison to other studies using full-pelvis models [3, 25]. Its application can nonetheless be justified as its principle is based on the theory of symmetric structures, described by Clements et al. [26], featuring comparable construct behaviour to other full-pelvis models. Moreover, SI joint forces were calculated and implemented in the model, resulting in a more physiological relation between the applied axial load and lateral bending moment. Hence, our test setup can be considered as reliable and reproducible.

The present study showed more movements and less stiffness when the SI joint is non-anatomically reduced. It is therefore mandatory to reduce the SI joint as good as possible in order to increase the fixation strength and avoid unstable instrumentations, which may result in secondary SI joint dislocation with poor clinical outcomes. Moreover, it was shown that there are no considerable differences between the fixation techniques with obliquely and transversely placed screws regarding SI joint stability in the presented model.

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