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A Regularized Functional Method to Determine the Hip Joint Center of Rotation in Subjects with Limited Range of Motion

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Abstract

The symmetrical center of rotation estimation (SCoRE) is probably one of the most used functional method for estimating the hip join center (HJC). However, it requires of complex multi-plane movements to find accurate estimations of HJC. Thus, using SCoRE for people with limited hip range of motion will lead to poor HJC estimation. In this work, we propose an anisotropic regularized version of the SCoRE formulation (RSCoRE), which is able to estimate the HJC location by using only standard gait trials, avoiding the need of recording complex multi-plane movements. RSCoRE is evaluated in both accuracy and repeatability of the estimation as compared to functional and predictive methods on a self-recorded cohort of fifteen young healthy adults with no hip joint pathologies or other disorders that could affect their gait. Given that, no medical images were available for this study, to quantify the global error of HJC the SCoRE residual was used. RSCoRE presents a global error of about 12 mm, similarly to the best performance of SCoRE. The comparison of the coordinate's errors at each coordinate indicates that HJC estimations from SCoRE with complex multi-plane movements and RSCoRE are not statistical signifi-

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cantly different. Finally, we show that the repeatability of RSCoRE is similar to the rest of the tested methods, yielding to repeatability values between 0.72 and 0.79.

In conclusion, not only the RSCoRE yields similar estimation performance than SCoRE, but it also avoids the need of complex multi-plane movements to be performed by the subject of analysis. For this reason, RSCoRE has the potential to be a valuable approach for estimating the HJC location in people with limited hip ROM.

Keywords: Hip joint center, Functional method, Ridge regression, Gait analysis.

1. Introduction

Hip joint center (HJC) is used to define the geometry of the thigh segment which affects the hip and knee joint kinematics computed in gait analysis (Stagni et al., 2000; Kainz et al., 2017a). Since the HJC cannot be palpated, its location must be estimated by using regression approaches (called predictive methods) or functional methods from either marker data trials or medical images techniques (Kainz et al., 2017b). Regardless the method used to estimate the HJC location, for further built biomechanical models of human gait, such an estimate must be as accurate as possible (Bahl et al., 2019; Meng et al., 2019; Leboeuf et al., 2019).

In particular, the so-called functional methods rely on a multi-plane movement with large hip range of motion (ROM) (Kainz et al., 2015). Although, functional methods have shown to have better performance and more reliable results in the estimation of HJC than other methods (Leardini et al., 1999; Piazza et al., 2001; Schwartz and Rozumalski, 2005; Ehrig et al., 2006; Kainz et al., 2015), the goodness in the estimation requires the subject to perform a complex movement task. This undoubtedly represents a limitation when it is used in subjects with limited hip ROM, commonly found in clinical settings (Camomilla et al., 2006; Kainz et al., 2015).

Several functional methods have been proposed in the literature to compute the HJC (Leardini et al., 1999; Piazza et al., 2001; Gamage and Lasenby, 2002; Schwartz and Rozumalski, 2005; Ehrig et al., 2006). Most probably, the combination of accurate results with the fast computational time together with its implementation in one of the most important commercial software (Nexus from Vicon Motion Systems Ltd, Oxford, UK) had made the symmetrical center of rotation estimation (SCoRE) (Ehrig et al., 2006) with a Procruster algorithm be widely adopted in clinical settings (Rozumalski et al., 2013)

Since the performance of functional methods in estimating HJC are sensitive to the complexity of the calibration movement task used (Meng et al., 2019), many studies have concluded that the multi-plane StarArc movement proposed by Camomilla et al. (2006) (Siston and Delp, 2006; Kainz et al., 2015) is the best calibration movement. Thus, accurate HJC estimation based on SCoRE for people with limited ROM is still an open challenge in the biomechanical community.

In this work, we proposed an anisotropic regularized version of the SCoRE formulation, which is able to estimate the HJC location by using just standard gait trials, avoiding the need of recording complex multi-plane movements. The results show that our regularized SCoRE method with standard gait trials is able to achieve similar HJC estimation as compared to SCoRE with StarArc movements. These findings are important for the clinical biomechanical community working with subjects with limit hip ROM, narrowing a gap between functional methods and subject-specific ability of movement.

2. Materials and Methods

2.1. Participants and data collection

Fifteen young healthy adults (6 males, 9 females; mean ± SD age: 26.4 ± 3.9 *years*; height: 171.2 ± 9.6 *cm*; BMI: 24.8 ± 3.2 kg/m^2) with no hip joint pathologies or other disorders that could affect gait, were recruited. All participants gave informed, written consent prior to participation. The study protocol was approved by the Ethics Committee from Technical Research Center (Santa Fe, Argentina) at National Scientific and Technical Research Council. Participants were equipped with 8 markers to track the position of the pelvis and thigh on their dominant limb according to Figure 1.

An optical motion capture system Flex 13 OptiTrak (NaturalPoint, Corvallis, Oregon USA) with 8-cameras operating at 120 Hz was used to acquire the marker trajectories. Each participant was tested by the same rater, who performed the markers placement and collected the motion capture data. Testing was conducted on two sessions separated by one week. For each testing session, participants starting from a static standing calibration trial, were asked to perform six trials of each standard functional movement tasks (Cross, Arc, Star and StarArc as described in Camomilla et al. (2006)) and six gait trials at self-selected comfortable walking speed (session 1 walking speed: 0.857 ± 0.096 ms^{-1}, session 2 walking speed: 0.861 ± 0.099 ms^{-1}). A gait trial was considered successful if there were two consecutive heel contacts into the acquisition volume. For more details of movement tasks and hip ROM performed in each session see Appendix A.

2.2. Motion capture data post-processing

To reduce the effect of soft tissue artifacts for improving the accuracy and repeatability of HJC estimation (Taylor et al., 2010; Rozumalski et al., 2013), the Procruster algorithm 'Optimal Common Shape Technique' (OCST) proposed by Taylor et al. (2005) was applied to define a rigid body constraint. For better performance of the optimization process, the three-dimensional markers coordinate were defined positive for all movements task.

2.3. The regularized symmetrical center of rotation estimation

Anisotropic regularization is a technique commonly used to point-wise penalize the solution accordingly to a-priori knowledge of the problem at hand (Peterson et al., 2017; Ibarrola et al., 2017). In this work we serve of such property to construct a regularized version of the SCoRE method proposed by Ehrig et al. (2006), which we call RSCoRE. Roughly speaking, the SCoRE method is equivalent to solving the following over-determined linear least squares problem $A\mathbf{c} = \mathbf{b}$, where $A = [R, \ -S]$ accounts for the resulting matrix after stacking the rotation matrix of both involved segments, and $\mathbf{b} = [\mathbf{d}, \ -\mathbf{t}]^T$ is a vector accounting for the concatenation of the translation vectors of both involved segments. Note that $\{R, \mathbf{d}\}$ and $\{S, \mathbf{t}\}$ are the rotations matrix and translations vector from local segment coordinates to a global coordinates system of each involved segment, respectively (Ehrig et al., 2006). From the regression viewpoint, SCoRE involves solving an unconstrained minimization problem (1):

$$\min_{\mathbf{c}\in\mathbb{R}^6} \|\mathbf{b} - A\mathbf{c}\|^2 \,, \tag{1}$$

where $\mathbf{c} \in \mathbb{R}^6$ is the resulting vector whose first and last three elements represent the center of rotation at each segment local coordinate system, denoted by $\mathbf{c}_1$ and $\mathbf{c}_2$, respectively. Then, the optimal center of rotation $\mathbf{c}^* \in \mathbb{R}^3$ is calculated by taking the mean between $\mathbf{c}_1$ and $\mathbf{c}_2$. For more information about the SCoRE method we refer to (Ehrig et al., 2006).

By inspecting (1) it is clear that the prediction of $\mathbf{c}^*$ is sensitive to the conformation of the matrix A, i.e. to the rotation information at each segment. Thus, it is not surprising then that when SCoRE is fed with simple movements (i.e. movements without large hip ROM) the location of HJC is no longer reliable (Meng et al., 2019). Given that standard gait involves multi-plane movements but with limited hip ROM, we can think of this problem as a sub-representation problem in the non-sagittal planes. In this direction, we can “amplify” the ROM in the two less representative (out of the three) axes. For doing so, we propose the following anisotropic regularized SCoRE (RSCoRE) formulation:

$$\min_{\mathbf{c}\in\mathbb{R}^6} \|\mathbf{b} - A\mathbf{c}\|^2 + \lambda\|D\mathbf{c}\|^2, \quad (2)$$

where λ is a positive constant, called regularization parameter and D is a 6×6 diagonal matrix whose elements are constructed based upon the range variation of each segment at each axis. Note that, similarly to $\mathbf{c}$, the first and last three diagonal elements of D correspond to each involved segment, respectively. Details about how D is constructed as well as how the RSCoRE can be computationally implemented are described in Appendix B.

2.4. Data analysis

Experiments were conducted on Python 3.6. The RSCoRE was implemented as a Ridge regression problem (Marquardt and Snee, 1975) using scikit-learn (Pedregosa et al., 2011). The best regularization parameter λ was found as the minimizer of the ℓ_∞-norm between the estimated and the true $\mathbf{b}$ vector in a grid-search approach (see Appendix B). Accuracy and repeatability of HJC estimation were evaluated for both SCoRE and RSCoRE methods at various calibration movement tasks, namely Gait, Cross, Arc, Star and StarArc for SCoRE and only Gait for RSCoRE. Our functional method for locating HJC was also compared to the predictive method estimation proposed by Harrington et al. (2007) on page 599. This method uses the leg length as well as the pelvis' deep and width anthropometric measures in their HJC estimation formulation.

Accuracy was evaluated in global and individual Cartesian coordinates. To quantify the global accuracy of HJC estimation the SCoRE residual was used (Ehrig et al., 2011). For detail see Appendix C.

Statistical analyses between the different HJC estimations were performed by a paired Wilcoxon test with Bonferroni correction at a significance level of 95%.

To evaluate HJC repeatability at each coordinate at various movement tasks and scenarios, the variability inter-subject, variability inter-session (of the same tester) and inter-session-trial measured by the intra class correlation (ICC), were evaluated as described in Chia and Sangeux (2017).

3. Results

Global HJC error of RSCoRe with a simple movement task (mean and standard deviation between two sessions: 12.09 ± 0.51 mm) yielded either smaller or similar error that the best performance of SCoRE (Figure 2). As expected, the HJC estimation via SCoRE improved as long as the complexity movement increased (values found to be 22.38 ± 2.46 mm for Gait and 12.52 ± 2.15 mm for StarArc.

By analyzing the HJC estimation for each coordinate between the different tested methods (predictive and functional methods), statistical differences were only found between SCoRE with StarArc and SCoRE with Gait trials, and between SCoRE with StarArc and the tested predicted method, as depicted in Figure 3. In addition, RSCoRE coordinate estimations showed that the absolute deviation with respect to the estimation performed by SCoRE with StarArc movement task is less than 0.5 mm in at least the 80% of the cases (Figure 4). For the sake of comparison, Figure 4 also shows such absolute deviations for SCoRE with no StarArc movement task and the tested predicted method.

While RSCoRE achieved similar variability inter-subject in the x-coordinate as compare to SCoRE and the tested predicted method, this was not the case for the under-representative coordinates (y and z). By analyzing the inter-sessions variability as well as the ICC values, we see that RSCoRe was still able to reach values between ($0.72 \leq ICC \leq 0.79$) compared to ($0.83 \leq ICC \leq 0.87$) for SCoRE and ($0.84 \leq ICC \leq 0.90$) for the tested predicted method (Table 1).

Table 1: Repeatability results at each coordinate for SCoRE and RSCoRE at different movement tasks. σ^2_{subj} and σ^2_{sess} represent the variability inter-subject and the variability inter-session calculated from the mean HJC value, respectively. ICC accounts for the variability inter-session-trial.

	Methods	Task	σ^2_{subj} ($\times 10^3$)	σ^2_{sess} ($\times 10^3$)	ICC
x-coordinate	SCoRE	Gait	3.72	0.55	0.87
		Cross	3.13	0.78	0.77
		Arc	4.77	1.06	0.78
		Star	4.08	0.62	0.87
		StarArc	4.12	0.69	0.84
	Harrington	-	3.44	0.48	0.88
	RSCoRE	Gait	3.26	0.87	0.75
y-coordinate	SCoRE	Gait	1.82	0.27	0.86
		Cross	1.29	0.35	0.74
		Arc	1.79	0.86	0.59
		Star	1.58	0.34	0.82
		StarArc	1.49	0.33	0.81
	Harrington	-	0.99	0.11	0.90
	RSCoRE	Gait	2.26	0.49	0.79
z-coordinate	SCoRE	Gait	12.23	2.37	0.83
		Cross	13.12	2.78	0.82
		Arc	12.86	2.69	0.82
		Star	13.42	2.73	0.83
		StarArc	13.23	2.72	0.83
	Harrington	-	12.34	2.27	0.84
	RSCoRE	Gait	14.22	4.37	0.72

4. Discussion

In this work, an anisotropic regularized version of SCoRE (RSCoRE) was formulated to estimate the HJC position using simple movement task like standard gait trials. Overall, the results showed that our proposed RSCoRE method is able to achieve similar or even better performance indices than SCoRE with complex movement tasks.

Accuracy for the HJC estimations was evaluated for both global and individual coordinates errors. *In vivo* studies in a young healthy adults population showed that SCoRE got an average global error of 7.2 to 15.5 mm when StarArc was used as the calibration movement task (Ehrig et al., 2011; Sangeux et al., 2011, 2013, 2014). Interestingly, the highest error was showed (more than 30 mm on average) for the case of reduced hip ROM (Sangeux et al., 2014). In our young healthy adult sample population, the global error results (Figure 2) achieved by SCoRE showed that as movement task complexity increased (from Gait to StarArc), the estimation error decreased, in accordance with (Camomilla et al., 2006). In particular, average global error of 12.5 mm and 22.4 mm were found for SCoRE with StarArc and Gait trials, respectively. By inspecting the results achieved by our RSCoRE method, it is interesting to point out that the global error was about 12 mm, error value that lies in the range of SCoRE with StarArc.

The comparison of the coordinate error shown in Figure 3 indicated that HJC estimations from SCoRE with StarArc and RSCoRE were not statistical significantly different for the anterior-posterior (x-coordinate), inferior-superior (y-coordinate) and medial-lateral (z-coordinate) coordinates. Statistical differences were found only between SCoRE+Gait and SCoRE+StarArc (with exception of x-coordinate in session 1), and the tested predictive method and SCoRE+StarArc (with exception of x-coordinate).

The comparison between biomedical images and the SCoRE with StarArc estimation of HJC performed by Sangeux et al. (2011, 2013, 2014) showed that SCoRE presented positive deviations in the lateral and anterior coordinates and negative deviations for the superior coordinate, with respect to the true HJC location. In this way, as shown in Figure 4, RSCoRE presented lower values for the lateral and anterior coordinates while a higher value for the superior coordinate, as compared to SCoRE with StarArc. This deviation analysis could explain the improvement shown by RSCoRE in the global error (Figure 2). However, since no biomedical images were registered in this study, these results should be interpreted with caution. Future plans include the validation of a such conjecture with biomedical images.

Many studies (Taylor et al., 2010; Bahl et al., 2019) showed that more reliable results can be achieved by the SCoRE method with OCST, since it becomes less sensitive to marker placement and measurement session, as compared to predictive methods. However, the study performed by Kainz et al. (2017b) showed that the opposite behavior can be achieved when the data collection is performed by the same tester, i.e. predictive methods seems to be more reliable than functional methods. For this reason, for analyzing the repeatability of the methods, we relied on the inter-subject, inter-session and inter-trial-session variability, as shown in Table 1. In accordance with Kainz et al. (2017b), and since our study also comprised the same tester for data collection, the predictive tested method showed to be more reliable than functional methods with $0.84 \leq ICC \leq 0.90$. Also, these results indicated that SCoRE and RSCoRE were equally repeatable in term of the inter-subject and inter-session variability for each coordinate. It is important to mention here that, although SCoRE had the highest repeatability ($0.83 \leq ICC \leq 0.87$) with gait trials, it also presented the highest errors in HJC estimation (Figs. 2 and 3). By analyzing those values for RSCoRE, we noticed that a very good repeatability for all coordinates ($0.72 \leq ICC \leq 0.79$) can be found while keeping global error to the minimum (Figure 2). Thus, RSCoRE seems to be able to reach very good values to ensure accuracy and repeatability in settings where several tester are involved.

As pointed out before, one limitation of this study is that not biomedical images were available to set the gold standard. But here, and similarly to other studies (Taylor et al., 2010; Ehrig et al., 2011; Heller et al., 2011) where images were not available, SCoRE residual was used to assess the accuracy of functional methods (Kainz et al., 2015). Another limitation of this study is that the cohort data consisted of young healthy adults of BMI: $24.8 \pm 3.2\ kg/m^2$. Future works will also focus on the inclusion of a more diverse demographic population, and on the study of new strategies to optimize the anisotropic matrix when working with pathological populations with limited hip ROM. Despite these limitations, this work shows for the first time that by means of a regularized version of SCoRE, the recording of extra calibration movement tasks can be completely avoided, being of highly importance for clinical settings.

In conclusion, an anisotropic regularized version of the well-known SCoRE method was formulated, named RSCoRE. The RSCoRE method not only avoids the need of complex movement task to be performed by the subject of analysis, but also yields to similar or even better accuracy and repeatability values as compared to SCoRE with StatArc movements. These findings suggest that RSCoRE could be a valuable solution for estimating the HJC location in people with limited hip ROM.

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Contributions

EPR was responsible for the conception, design of the research, conduct the data collection, writing the code to process the data, interpretation of the results and writing and revision of the manuscript for important intellectual content. VP was responsible for the design of the research, assisted EPR in the mathematical approach and code implementation, and for the edition and revision of the manuscript. Both authors read and approved the final version of the manuscript.

Conflict of interest

The authors declare that they do not have a conflict of interest.

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Figure 1: Schematic marker set location. Four Markers retroreflective spherical markers (14 6574mm diameter) on specific palpable bone landmarks were placed; three for the pelvis, the right and the left superior iliac spine (RASIS and LASIS, respectively) and SACRUM in the middle of the right and the left posterior superior iliac spine; and for the knee at the lateral epicondyle (KNEE). Additional virtual marker (VKNEE) on the knee at the medial epicondyle (Leardini et al., 2007) and a thigh marker cluster (CT1, CT2, CT3) were included (Begon et al., 2007). The thigh cluster was placed lateral on the distal third of the thigh

Figure 2: Global HJC error estimation for the SCoRE and RSCoRE methods for the two registered sessions. The SCoRE method shows an improvement in HJC estimation as the complexity of the task increases.

Figure 3: HJC coordinates estimated by SCoRE in different scenarios, RSCoRE and the tested predictive method (Harrington). Session 1: solid bars, session 2: striped bars. From top to bottom: x, the anterior-posterior coordinate, y, the inferior-superior coordinate and z, the medial-lateral coordinate. Each coordinate was normalized by the participant leg length (Hof, 1996). Here $* : 1.00e-02 < p \leq 5.00e-02$ and $** : 1.00e-03 < p \leq 1.00e-02$ denote p-values in the Wilcoxon test (paired samples) with Bonferroni correction.

Figure 4: HJC coordinates absolute deviation of SCoRE in different scenarios, RSCoRE and the tested predictive method (Harrington) with respect to SCoRE with StarArc. Δx: the anterior-posterior coordinate deviation; Δy: the inferior-superior coordinate deviation; and Δz: the medial-lateral coordinate deviation. Proportion of data bellow a 0.5 mm absolute deviation is specified at the top of the linear graph.

Appendix A. Description of the moment tasks

The precision and accuracy of the HJC location through functional methods has been shown to be sensitive to movement tasks using functional calibration movement. The study performed by Camomilla et al. (2006) analyzed the performance of functional methods with several movement tasks. In this way, movement tasks described in Table A.1 were performed for the participants during data acquisition.

Table A.1: Description of the moment tasks and ROM for each session performing in data collection. Cross, Arc, Star and StarArc as proposed by Camomilla et al. (2006).

		Hip ROM (deg)	
Movement	Description	session 1	session 2
Gait	Gait trial between two consecutive heel contacts.	23.47 ± 1.64	27.32 ± 7.05
Cross	Movement of the lower limb relative to the pelvis: full flexion, neutral position, full extension, neutral position, full abduction, neutral position.	45.31 ± 3.35	40.86 ± 3.75
Arc	Movement of the lower limb relative to the pelvis: full flexion, half circumduction to full extension, neutral position.	40.08 ± 3.59	35.90 ± 2.76
Star	Seven flexion-extension/ abduction-adduction combined movements from the neutral position within the perimeter drawn in the Arc movement.	42.46 ± 4.22	39.49 ± 2.47
StarArc	Star movement followed by Arc movement.	43.35 ± 4.82	45.08 ± 10.27

Appendix B. Anisotropic Regularisation within SCoRE formulation

While only limited space was available for presenting details of the mathematical formulation of the anisotropic regularized version of SCoRE (RSCoRE) and it computational implementation, more complete details are presented in the following.

The regularized symmetrical center of rotation estimation

In this study, an anisotropic regularized formulation of the symmetrical center of rotation estimation (SCoRE) algorithm was proposed. The SCoRE method assumes that the joint center is stationary in each segment's local coordinate system (Ehrig et al., 2006). So, if the rotation matrix ($A = [R, \ -S]$) and translation vector ($\mathbf{b} = [\mathbf{d}, \ -\mathbf{t}]^T$) from the local segment coordinate system to global system are known, the optimal HJC can be obtained by solving the following least-squares optimization problem:

$$\min_{\mathbf{c}\in\mathbb{R}^6} \|\mathbf{b} - A\mathbf{c}\|^2 \ , \tag{B.1}$$

where $\mathbf{c} \in \mathbb{R}^6$ is the resulting vector whose first and last three elements represent the center of rotation at each segment local coordinate system, denoted by $\mathbf{c}_1$ and $\mathbf{c}_2$, respectively. Given the nature of (B.1), the prediction of the optimal center of rotation $\mathbf{c}$ is sensitive to the conformation of the matrix A, i.e. to the rotation information at each point segment.

Regularization techniques are commonly used to impose desired properties in the solution. Different regularization terms can be added to the ordinary least square functional described in (B.2). For instance, when the ℓ_2-norm is added to the cost function, large values of $\mathbf{c}$ will be penalized, as follows:

$$\min_{\mathbf{c}\in\mathbb{R}^6} \|\mathbf{b} - A\mathbf{c}\|^2 + \lambda\|\mathbf{c}\|^2 \ , \tag{B.2}$$

where $\lambda > 0$ is a problem parameter, called regularization parameter. In this context, regularization gives a compromise between solving the equations (i.e., making $\|\mathbf{b} - A\mathbf{c}\|^2$ zero) and keeping $\mathbf{c}$ of reasonable size.

Given that standard gait trial involves multi-plane movements but with limited hip ROM, we can think of this problem as a sub-representation problem in the non-sagittal planes. In this way, we would like the solution to take more in consideration the information of some axis while neglecting such information in the other ones. From the mathematical viewpoint, this can be formulated by point-wise weighting the solution in an anisotropic way. Let $\mathbf{c}$, $\mathbf{b}$ and A be as before, and let D be a diagonal matrix whose elements anisotropically penalize the solution, then, the anisotropic regularized SCoRE (RSCoRE) formulation can be described as follows:

$$\min_{\mathbf{c}\in\mathbb{R}^6} \|\mathbf{b} - A\mathbf{c}\|^2 + \lambda\|D\mathbf{c}\|^2 . \tag{B.3}$$

The anisotropy matrix D in equation (B.3) is a diagonal matrix built so as to "applify" the ROM in the two less representative axes (inferior-superior: $z-$coordinate, and medial-lateral: $x-$coordinate), while keeping constant the other one. For doing so, we propose to construct the elements of D based upon some available a-priori information given in the data (Peterson et al., 2017), i.e. in the range variation of each segment at each plane (B.4):

$$D = \begin{pmatrix} \sqrt{d_{z1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & \sqrt{d_{x1}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sqrt{d_{z2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sqrt{d_{x2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \tag{B.4}$$

where d_{xj} and d_{zj} represents the interquartile range (being equal to the difference upper and lower quartiles) of the $x-$coordinate and $z-$coordinate of the segment centroid, for $j = 1$: pelvis segment, and $j = 2$: thigh segment, respectively.

Given that D^{-1} exists, the RSCoRE formulation in Eq. (B.3) can be rewritten as a Ridge regression problem (Marquardt and Snee, 1975):

$$\hat{\boldsymbol{\alpha}} = \arg\min_{\boldsymbol{\alpha}\in\mathbb{R}^6} \|\mathbf{b} - AD^{-1}\boldsymbol{\alpha}\|^2 + \lambda\|\boldsymbol{\alpha}\|^2, \tag{B.5}$$

where $\hat{\mathbf{c}} = D^{-1}\hat{\boldsymbol{\alpha}}$.

With RSCoRE so defined in Eq. (B.5) any Ridge regression implementation can be used. In particular, in this work the Ridge regression implementation of scikit-learn (Pedregosa et al., 2011) was used (Python 3.6). The regularization parameter was set after a grid-search over the set $I_\lambda = (0, 2]$ taken steps of 0.1. The best regularization parameter λ^* was then the value at which the ℓ_∞-norm between the estimated and the true $\mathbf{b}$ vector was minimum.

Appendix C. Global error estimation of HJC: residuum of linear least squares problem

SCoRE is a functional method to determine the center of rotation of spherical joints. In particular, the SCoRE method can be thought as an optimization problem with no constraints, as shown Eq. (B.1), that seeks to solve the following linear system: $A\mathbf{c} = \mathbf{b}$. The associated normal equation to Eq. (B.1) is given by:

$$(A^T A)\mathbf{c} = A^T\mathbf{b}. \tag{C.1}$$

Otherwise, the RSCoRE method is an anisotropic regularized version of the SCoRE. Equation (B.3) is known in the literature as Tikhonov regularization (Zhang and Huang, 2013). The normal equations associated to Eq. (B.3) are given by

$$\left(A^T A + \lambda D^T D\right)\mathbf{c} = A^T\mathbf{b}\ . \tag{C.2}$$

Since the motion of the segments can not perfectly describes spherical circumvention around a common center, both center representations (i.e. $\mathbf{c}_{1,i} = R_i\mathbf{c}_1 + \mathbf{d}_i$, $\mathbf{c}_{2,i} = S_i\mathbf{c}_2 + \mathbf{t}_i$) will not coincide for all time frames i. For this reason, the authors in (Ehrig et al., 2011) proposed to use the magnitude of the residual error $\mathbf{r} = A\hat{\mathbf{c}} - \mathbf{b}$ of Eq. (C.1) as an useful measure for the expected global error for HJC estimation, where $\hat{\mathbf{c}}$ denotes the estimated least squares solution. In this way, Ehrig et al. (2011) showed that the global error of the HJC estimation (err) have a direct relationship with $\mathbf{r}$ for any ROM by the following equation:

$$err = \frac{\|\mathbf{r}\|}{2}\left(1 + \frac{2}{\sqrt{6}}\sqrt{\sum_{i=1}^{6}\frac{1}{s_i^2}}\right)\ , \tag{C.3}$$

where s_i with $i = 1, 2, \ldots, 6$ are the singular values of the coefficient matrix A.

When regularization is applied, the linear system in (C.1) no longer holds. It is easy to see then from Eq. (C.2), that for the RSCoRE method the singular values involved in (C.3) should be calculated from $A_r = \left(A^T A + \lambda D^T D\right)$.

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Abstract:

The symmetrical center of rotation estimation (SCoRE) is probably one of the most used functional method for estimating the hip join center (HJC). However, it requires of complex multi-plane movements to find accurate estimations of HJC. Thus, using SCoRE for people with limited hip range of motion will lead to poor HJC estimation. In this work, we propose an anisotropic regularized version of the SCoRE formulation (RSCoRE), which is able to estimate the HJC location by using only standard gait trials, avoiding the need of recording complex multi-plane movements. RSCoRE is

evaluated in both accuracy and repeatability of the estimation as compared to functional and predictive methods on a self-recorded cohort of fifteen young healthy adults with no hip joint pathologies or other disorders that could affect their gait. Given that, no medical images were available for this study, to quantify the global error of HJC the SCoRE residual was used. RSCoRE presents a global error of about 12 mm, similarly to the best performance of SCoRE. The comparison of the coordinate's errors at each coordinate indicates that HJC estimations from SCoRE with complex multi-plane movements and RSCoRE are not statistical significantly different. Finally, we show that the repeatability of RSCoRE is similar to the rest of the tested methods, yielding to repeatibility values between 0.72 and 0.79.

In conclusion, not only the RSCoRE yields similar estimation performance than SCoRE, but it also avoids the need of complex multi-plane movements to be performed by the subject of analysis. For this reason, RSCoRE has the potential to be a valuable approach for estimating the HJC location in people with limited hip ROM.

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Conflict of Interest Statement

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The authors declare not having any financial and personal relationships with other people or organisations that could inappropriately influence (bias) their work.

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