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Normal goniometric values to guide decision-making in lower-extremity rotational problems using support vector machine techniques

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Abstract

Torsional analysis of the lower extremities has become an integral part of the decision-making process in treating neuromuscular problems. Solid knowledge of normal development of torsional relationships is essential for treating musculoskeletal problems. As a prerequisite, a normal reference, meaning an objective and quantitative standard of measurement, must be available for comparison prior to making a suitable decision. The aim of this paper is to update normal goniometric values that could be used as a reference for clinical analysis and to discover unknown compensatory mechanisms between the involved segments. A systematic and coherent database made from almost 900 measurements of different parameters has been studied using a process of support vector data description (SVDD) to achieve our outlined targets. The aim is to produce updated decision-making support for clinicians working in the biomechanical exploration of the lower extremities.

Key words: support vector machines, decision-making, torsional analysis of the lower extremities, musculoskeletal problems

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1 Introduction

When performing biomechanical exploration, one of the most frequent sources of concern is related to alterations of the alignment of the lower limbs. As a result, torsional analysis of the lower extremities has become an integral part of the decision-making process when treating neuromuscular problems. Various studies have suggested that, aside from functional limitations and cosmetic concerns, abnormal gait or torsional misalignments may be risk factors for degenerative pathological effects on joints of the lower extremities [1,2]. Although there is a large amount of data on assessment methods and treatments for a variety of deformities, rotational problems in the transverse plane have been neglected due to the difficulty of assessment. Identification of the alterations and precise knowledge about the extent a given extremity is within or outside of some normal parameter value is a difficult task. Even today, despite technological developments, clinicians continually experience doubts regarding the normality of internal and external femoral rotations.

Nevertheless, solid knowledge of the normal development of torsional relationships is essential for treating musculoskeletal problems, and normal references, that is to say, objective and quantitative standard measurements are of crucial importance for comparison prior to making a decision.

In the 1980s, Staheli [3,4] provided a great deal of information on normal ranges of lower limb rotation. A small number of studies using various classical statistical techniques and small amounts of data have since been contributed to the subject [5–9]. Although, these normal ranges are interesting a priori, in practice they are not very helpful. One of the most frequent errors consists in applying normal values obtained for one technique outside of the precise context where those values were obtained. As an example, ranges of normality for a joint, such as the coxo-femoral, obtained under flexion cannot be extrapolated to the case of an extension of the same joint.

The aim of this paper is to update normal goniometric values that could be used as a reference for clinical analysis and to discover unknown compensating mechanisms between the involved segments. For this purpose we use a database made from almost 900 measurements of different parameters taken by the same clinician (the first author) during the last 15 years and including individuals with the necessary criteria to be included in the study. For this purpose, apparently normal individuals aged between 2 and 60 years were considered.

Currently, a number of approaches based on Intelligent Data Analysis and Machine Learning techniques have blossomed, and these have been shown to be more efficient than classical statistical techniques for a number of problems involving certain types of data. In this paper, we focus on a non-parametric clustering methodology based on support vectors (SVC). The proposed algorithm can deal with noise and outliers. Precisely, it is these outliers that may provide richer information for the study.

Support vector machine (SVM) is a popular pattern classification method with many application areas. SVM shows its outstanding performance in high-dimensional data classification. SVM was first proposed by Vapnik [10] and has recently been applied in a range of problems including pattern recognition, bioinformatics, and clustering. The process of clustering is based on kernel methods that avoid explicit calculations in the abovementioned high-dimensional feature space and making clustering more efficient. In addition, our proposal has the computational advantage of relying on an SVM quadratic optimisation that reaches global solutions.

The rest of the paper is organised as follows. Firstly, the materials and methods are presented. The results obtained are then provided. Finally, a discussion and conclusions close the paper.

2 Materials and method

As stated in the abstract, the aim of this paper is to produce an updated decision-making support for clinicians interested in the biomechanical exploration of the lower extremities. We have used a clinical goniometer from the outset. Various studies [11,12] support the view that conventional manual goniometers can be used with confidence, provided that the physiotherapist is experienced in the use of goniometry. This old technique is simple, reproducible, economical, fast, and efficient when measuring the various ranges of joint mobility. Even though other standardised techniques (RX, computerised tomography, and the electromagnetic tracking system) provide arguably greater accuracy, some of these techniques are harmful, others expensive, and others take longer to produce results. The appropriate use of the goniometer circumvents these drawbacks and avoids unnecessary tests. The database has been compiled by the same clinician (JMBJ) during more than 15 years for the whole series of measurements. We consequently claim that the bias of the data is negligible. Moreover, the same goniometer was used in all cases. More than four thousand coherent and systematic measurements have been gathered over the years. In this study, we will use a sample of 871 records collecting data from individuals with ages ranging from 2 to 60 years. The measured variables are: ’let’, ’ret’, ’lit’, ’rit’, ’lef’, ’ref’, ’lif’, ’rif’; the first letter refers to left or right; the second means external or internal; finally, the third letter is for tibia or femur. The criteria used for inclusion in the database were: not having undergone pathological antecedents of lower limbs, femoral luxations, traumatic antecedents, and metatarsus aductus (the final criteria excludes tibial rotation measurements due to their technical difficulty). Patients were asked for permission to be included in the study and were selected among male and female basketball players, personnel of the Hospital 'La Fé' of Valencia (Spain), and other patients who attended the private consulting room.

2.1 Data adquisition

Regarding the possibility of measuring internal and external femoral and tibial rotations with the lower limb flexed or stretched, dissimilar opinions are found in the literature, and there is no agreement about performing the measurements with the patient prone or supine [13–16]. The American Academy of Orthopaedic Surgeons advocates data acquisition under hip extension, since the hip is closer to its functional position during perambulation (shod gait).

In our case, data was obtained by following the Stanley Hoppenfeld protocol [17] to measure both internal and external femoral and tibial rotations. With the patient sitting down, the hip in flexion, and the legs hanging, the patient is asked to stretch his or her back. In this position the hip is completely stabilised. It is important that the patient does not move during measurements to avoid producing measurement errors. From a position in front of the patient, the clinician uses one hand to stabilise one knee of the patient. With the other hand, a displacement towards the exterior is performed, avoiding any movement by the patient: this is the internal rotation. By displacing to the medial the external rotation is obtained. The goniometer is placed on the centre of the knee; then the leg in which the tibia is being displaced is held with the hand performing the displacement, and the other leg is vertical due to gravity. The obtained angle is then observed and annotated (see Figure 1a, 1b).

Fig. 1. Measuring

The technique used for tibial measuring is also described by Hoppenfeld et al. [17]. Starting from the position described in the previous paragraph, sitting down with hanging legs, the sub-astragaline joint is neutralised. One leg of the goniometer is then aligned along the foot with the centre in the calcaneus going past the metatarsian. The other leg of the goniometer remains perpendicular to the body. The given angle is annotated (Figure 1c). Even though this technique may result rather complex at the beginning, it is quite fast after a little practice. This measurement is not made directly along the tibia, but along the angle formed by the tibia and the foot. The measurement is very accurate provided a neutralisation of the tibio-peronean-astragalin (TPA) joint is performed. The exception comes from individuals suffering from metatarsus aductus. These cases, as said before, have been excluded from the study.

Support vector clustering (SVC) was introduced by Ben-Hur et al. [18] to cluster the data set based on the theory of support vector machine (SVM). SVMs are a family of algorithms that solve a variety of learning and (non-linear) function estimation problems. They apply simple linear methods to the data in a high-dimensional feature space non-linearly related to the input space by a kernel function. One essential property of these kernel functions is that they can work with the data on this high-dimensional space without needing explicit computation. This so-called 'kernel-trick' adds simplicity to the SVM approaches, which combined with their adequate performance on a wide range of real-world learning problems (such as classification and regression) has added to their popularity.

SVC expands SVM to consider the problem of clustering. In the SVC algorithm, data points are usually mapped from the data space to a highly dimensional feature space using a Gaussian kernel. Throughout this paper, we will assume that the Gaussian kernel given by Equation 1 is used as a kernel function.

$$K(x_i, x_j) = e^{-q||x_i - x_j||^2} =< \phi(x_i) \cdot \phi(x_j) > . \tag{1}$$

$|| \cdot ||$ is the Euclidean norm, ϕ is the non-linear transformation to the feature space, and q is the width of the Gaussian kernel. The clustering level can be controlled by changes in this width parameter. As it is increased, the number of disconnected contours in the data space also increases, leading to an increasing number of clusters. In feature space we look for the smallest sphere that encloses the image of the data. This sphere is mapped back to the data space, where it forms a set of contours that enclose the data points. These contours are interpreted as cluster boundaries. SVC can deal with outliers by employing a soft margin constant that enables the sphere in feature space not to enclose all the points. Specifically, this sphere of centre a and radius R can be defined as $||\phi(x_j) - a|| \leq R^2 \ \ \forall j$.

Soft constraints may be incorporated by adding slack variables ξ_j:

$$||\phi(x_j) - a|| \leq R^2 + \xi_j, \ \ \xi_j \geq 0. \tag{2}$$

The problem can be solved introducing the Lagrangian as follows:

$$L = R^2 - \sum_j (R^2 + \xi_j - ||\phi(x_j) - a||^2)\beta_j - \sum \xi_j \mu_j + C \sum \xi_j, \tag{3}$$

where β_j and μ_j are Lagrange multipliers, C is a constant defined by the user which is included in the penalty term $C\sum\xi_j$. To solve this Equation 3, we set to zero the derivative of L with respect to R, a and ξ_j, respectively:

$$\sum_j \beta_j = 1, \tag{4}$$

$$a = \sum_j \beta_j \phi(x_j), \tag{5}$$

$$\beta_j = C - \mu_j. \tag{6}$$

By the Karush-Kuhn-Tucker (KKT) complementary conditions of Fletcher [19], we have that

$$\xi_j \mu_j = 0, \tag{7}$$

$$(R^2 + \xi_j - ||\phi(x_j) - a||^2)\beta_j = 0. \tag{8}$$

By rewriting these relations we may solve their associated dual problem:

$$\max W = \sum_j \phi(x_j)^2 \beta_j - \sum_{i,j} \beta_i \beta_j \phi(x_i) \cdot \phi(x_j) \tag{9}$$

s. t.

$$0 \leq \beta_j \leq C,\, j = 1, \ldots, N. \tag{10}$$

Only those points that follow the constraints especified in Equation 10 lie on the boundary of the sphere and are called support vectors (SV). Points with $\beta_j = C$ lie outside and are called bounded support vectors (BSV). Following the SV methods [10] we can represent the dot products, $\phi(x_i) \cdot \phi(x_j)$, using an adequate Mercer kernel, $K(x_i, x_j)$. Thus the Lagrangian can be rewritten as:

$$\max W = \sum_j K(x_i, x_j)\beta_j - \sum_{i,j} \beta_i \beta_j K(x_i, x_j) \tag{11}$$

The distance of the image of one point, x, from the centre of the sphere is $R^2 = ||\phi(x) - a||^2$; taking into account Equation 5 we have:

$$R^2 = K(x, x) - 2\sum_j \beta_j K(x_i, x) + \sum_{i,j} \beta_i \beta_j K(x_i, x_j). \tag{12}$$

The radius of the sphere is:

$$R = \{R(x_i)|\ x_i \text{ is a support vector}\}. \tag{13}$$

This radius may be interpreted as cluster boundaries. In view of Equation 13, SVs lie on cluster boundaries, BSVs are outside, and all other points lie inside the clusters.

The cluster description algorithm does not differentiate between points that belong to different clusters. We use a geometric approach involving $R(x)$ to achieve this differentiation. The clustering rule can be represented as the adjacency matrix of components (i, j) defined by Equation 14 given two points of the data x_i and x_j and R.

$$A_{ij} = \begin{cases} 1 \ \forall \text{ point}, x_k, \text{ between } x_i \text{ and } x_j \text{ such that } R(x_k) \leq R \\ 0 \text{ otherwise.} \end{cases} \tag{14}$$

All data points are checked to assign a specific cluster. In addition, outliers are accommodated by enabling the minimal sphere to exclude several data point images, employing soft margins. The R language [20] has been used in this study.

3 Results

After applying the SVC technique described in sub-section 2.2 three different clusters are clearly obtained. The first cluster gathers 93% of the registers, while the other two represent a mere 4% and 3%, respectively. The more influential (discriminating) variables are age and tibial rotations. The first cluster, clearly corresponds to normality, and is clearly related to high values of both left and right tibial external torsion. The second cluster is characterised by high tibial internal torsion and ages of between 22 and 49 years. Finally, the third cluster is strongly characterised by the low age of the individuals (mean = 10.7) and also by high tibial internal torsion. Figure 2 represents the three clusters according to their two principal components in an SVM clustering plot. The first principal component is explained by the age, while the second is inversely proportional to the femoral rotation.

Fig. 2. SVM clustering plot

Clusters may be graphically analysed by using the input scatter-plot matrix, which represents the internal pairwise relationships between the variables. In addition, the estimated density functions are represented for each variable on its diagonal. This matrix is symmetrical. For charts on the lower triangular part, non-linear regression curves are added. Figure 3 represent the scatter-plot matrix of the first cluster. The last column is perhaps the most important since it represents the distribution of all the variables versus age, which is on the abscissas axis. As can be easily observed, in all cases the measured variables decrease with age, more rapidly during the early years of life and more steadily afterwards. Other interesting aspects can be observed, however. For example, the linear relationship between variables 'let' and 'ret' or between 'lif' and 'rif', express the symmetry of individuals (graphs in positions (3,4) and (5,2) of Figure 3). Also, the compensating effect between external tibial and internal femoral rotations (positions (4,3) to (5,4)) is clearly observed.

Fig. 3. Scatter-plot matrix of the first cluster

Fig. 4. Normality ranges for left and right tibial rotation

In our study we will use the terminology recommended by the Pediatric Orthopaedic Society, as used by Staheli et al. [3] and all the studies on the subject; and consider normal those values not beyond two standard deviations from the mean (see Figure 4 for variables 'let' and 'ret'). Regarding rotational problems, we speak about 'rotational variations' in all the cases falling into the normal range, and 'torsional deformities' in cases falling outside of the normal range.

Even though a decreasing trend is observed for all individuals for all variables, it is worth noting that values are different for males and females. As an example, Figure 5 represents the variable 'rif' for both sexes. The trend is similar, but the average for males is slightly lower (about 7^o) than for females.

Fig. 5. Normality ranges for 'rif' and the effect on the gender

4 Discussion

We decided to obtain femoral and tibial rotations with the patient sitting down with a flexed hip. As a consequence, our results do not need to coincide with those of previous studies. However, our method produces more exact results for a number of reasons:

(1) The relaxation of ligament, capsular, and muscular structures enables greater mobility. We have attempted to measure the state of the joints with the least influence affecting the measurements.
(2) We achieve better measuring control since the hip is much more stable; at the same time, the joint limit is better observed because it is evident when the patient starts to move.
(3) Patients feel more comfortable, since many people do not feel comfortable in prone and/or supine positions.
(4) Measurements of tibial rotations, that is to say, of the calf-foot angle are better performed with a sitting patient since the TPA is better visualised.

According to Walter B. Greene [15] neonates present external rotation greater than the internal rotation with a total range of movement of about 171^o, in contrast with the $90\text{-}100^o$ observed in toddlers of more than one year. The revision performed by Y. H. Li et al. [16], shows that after birth a femoral anteroversion of about $30\text{-}40^o$ accompanied of a pronounced femoral external rotation, and associated with a compensating tibial internal torsion can be observed. A gradual decrease from the $30\text{-}40^o$ after birth until $10\text{-}15^o$ at adolescence is produced. The biggest decrease is usually observed before the age of 8 years [16].

According to Hoppenfeld et al. [17], normal values of rotations both in hip flexion and extension in adults are 'rif' $= 35^o$ and 'ref' $= 45^o$.

In [3] Staheli et al. observed a significant difference between sexes ($p < 0.05$) regarding femoral internal rotations of about 7^o; the average during infancy for 'rif' is 50^o ranging between 25^o and 65^o. Altinel et al. [14] observed differences ranging from 9^o in prone position to 13^o in supine position. In contrast with these values, other authors have not found significant differences regarding rotations [9], and others have not found significant anatomic differences [13].

Our results confirm the decrease of rotations as a function of the age as in all the previous works [3,15,4,16,21]. During childhood, the decrease of internal femoral rotations ('rif' and 'lif') is accompanied by a compensating inverse decrease of external tibial rotations ('ret' and 'let'). This effect, already reported in [22], is observed in Figure 3, as stated above. These data question the old conclusion by Staheli et al. [3] related to a persistent external tibial rotation. According to our graphs it can be easily observed that these variables, 'ret' and 'let', do not suffer significant variation with age. Finally, as observed in Figure 5, rotations in both male and female follow a decreasing trend; it is greater for females than for males, the difference being on average of 7^o at the age of 8, and 5^o when adult.

5 Conclusions

To the best of our knowledge there is no study regarding the subject this paper addresses using SVM and, at the same time, using a database with such a systematic and coherent volume of data that measures all the levels of the lower extremity. This makes it possible to develop a method for enhancing the applicability of our results. The method is based on a process of support vector data description (SVDD) for each cluster and this process enables our outlined targets to be achieved. The final accuracy of our proposed method outperforms traditional statistical methods, and it may be used as a supplementary method for techniques such as computerised tomography.

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