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Analysis and Improvement of Raimondi's Table for Measurement of Axial Vertebral Rotation

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Abstract: - Axial vertebral rotation (AVR) is essential in studying idiopathic scoliosis. The Raimondi method is one of the techniques used to measure AVR on two-dimensional medical images. This method employs a set of data ordered in a table known as Raimondi's table (RT) that was obtained experimentally. This research aims to analyze and eliminate the systematic errors in the data consigned in RT. We programmed a simplified software in C++ to automate the calculations. We applied a previously published equation and checked the values obtained against the original values of the RT to correct the AVR data. The error distribution in the set of 1530 values in the RT is Me (mean error) = 0.43 mm, SD (standard deviation) = 0.33 mm, Max (maximum value) = 2.11 mm, Q3 (third quartile) = 0.61 mm, median = 0.35 mm, Q1 (first quartile) = 0.18 mm, and Min (minimum value) = 0. The distribution of the error due to those errors is Me = 2.57º, SD = 3.8º, Max = 26º, Q3 = 2.53º, median = 1.18º, Q1 = 0.62º, and Min = 0º. The error in the RT values can produce a significant AVR measurement error (greater than 25% of the actual value) when the measured rotation is slight. The relative error decreases as the measured rotation becomes more outstanding. We can conclude that improving the data consigned in the RT allows us to measure the AVR on medical images of scoliosis with a lower bias error when using Raimondi's method.

Keywords: Accuracy, Measurement, Raimondi's tables, Scoliosis, Vertebral rotation.

I. INTRODUCTION

Axial vertebral rotation (AVR) is defined as the rotation of a vertebra around its longitudinal axis when projected onto the transverse image plane [1]. AVR is a fundamental parameter to correctly assess, prognosticate, monitor, and treat scoliosis [2–5].

Two-dimensional medical images, especially posteroanterior images of the whole spine in a standing position, continue to be the method of choice for diagnosing and monitoring scoliosis [6–8]. Several methods, such as Nash-Moe, Perdriolle, and Raimondi's methods, are available for assessing AVR in such medical imaging based on identifying the position of some vertebral anatomical structures and their relationships [9–13].

The Nash-Moe [9,10,14] and Perdriolle [15–17] methods are still the most used in clinical practice for measuring AVR on frontal X-rays of the spine. One of the main advantages of the Nash-Moe method is its quick use [17]. However, the drawback is that the measurement obtained is only an approximation of the AVR, as the method classifies the AVR only in five intervals (grades 0 to 4). The measurement method described by Perdriolle is the

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most widely used and measures AVR more accurately [11,15,18]. The Perdriolle torsiometer is affordable, non-invasive, and easy to use once some experience has been gained [18–20], and there is consensus in the literature on its accuracy and simplicity of use [21]. According to Richards' classic study [15], 53% of measurements are within 5º of true AVR, and the average error is 6º.

The system developed by Raimondi is also a popular method [12,16,22–25]. Raimondi's method is easy to use [16,26] and particularly recommendable for novel evaluators [27]. In addition, Raimondi's approach allows for measurements in 2º intervals of rotation [16], which looks more accurate than Perdriolle's method, which measures in 5º intervals [16,25,26]. Raimondi's method uses a set of ordered data, which is known as Raimondi's table (RT), to determine the AVR [12,22,23] (Table 1). In RT, the data of the same column corresponds to a particular width (D) of the vertebral body projected on the X-ray image (see Table 1).

Table 1. Simplified Raimondi's tables with data to obtain the axial vertebral rotation (Modification of: Raimondi and Prosperini (2007), La misurazione della rotaziones vertebrale nelle scoliosi. Esperienze a confronto.) [13]

2.3	2.4	2.5	2.6	2.7	…	7.8	**AVR = 2º**
2.6	2.7	2.8	2.9	3	…	9	**AVR = 4º**
2.9	3	3.1	3.2	3.4	…	9.8	**AVR = 6º**
3.2	3.3	3.4	3.6	3.7	…	10.5	**AVR = 8º**
3.5	3.6	3.8	3.9	4.1	…	11.7	**AVR = 10º**
3.7	3.8	4	4.2	4.3	…	12.8	**AVR = 12º**
3.9	4	4.2	4.4	4.6	…	13.9	**AVR = 14º**
4.1	4.2	4.5	4.7	4.9	…	15	**AVR = 16º**
4.3	4.5	4.7	4.9	5.2	…	16	**AVR = 18º**
4.5	4.7	5	5.2	5.5	…	17.3	**AVR = 20º**
4.9	5.1	5.4	5.7	5.9	…	18.8	**AVR = 22º**
5.3	5.5	5.8	6.1	6.4	…	20.1	**AVR = 24º**
5.7	6	6.3	6.6	6.9	…	21.7	**AVR = 26º**
6	6.4	6.7	7	7.4	…	23.1	**AVR = 28º**
…	…	…	…	…	…	…	**…**
17.5	18.3	19.2	20	20.9	…	61.5	**AVR = 60º**
D = 20	**D = 21**	**D = 22**	**D = 23**	**D = 24**	**…**	**D = 70**	

Table 1. Simplified Raimondi's tables. Each column shows a value of D (the width of the vertebral body projected on the X-ray image). The data correspond to the distances d (i.e., the distance between the center of the shadow of the pedicle furthest from the lateral side of the vertebral body and the lateral side of the vertebral body, in millimeters). Each pair of values (D, d) corresponds to a value of AVR (axial vertebral rotation) between 2º and 60º.

Within each column, the data corresponds to the distance (d) between the center of the shadow of the pedicle furthest from the lateral side of the vertebral body and this lateral side of the vertebral body (in millimeters). Each pair of values (D, d) corresponds to an AVR value between 2º and 60º.

The data contained in RT were obtained experimentally from thousands of measurements on educational and anatomical spines [13]. Consequently, the measurements obtained using this method involve systematic errors [13,25].

Our research aims to mathematically analyze the RT, detect systematic errors, and substitute with accurate values to increase the correctness of the RT.

II. METHODOLOGY

Hurtado-Aviles et al. [28] obtained a mathematical model from the distribution of empirical data in RT describing the information of RT in a theoretical manner, as shown in Equation (1). The authors used the equation to obtain the theoretical values of each datum d recorded in the RT and the error, in millimeters and degrees, of each datum d.

$$\mathrm{AVR} = \frac{20.22483 - 330.5077\left(\frac{D}{d}\right) + 33.46082\left(\frac{D}{d}\right)^2}{1 - 3.93825\left(\frac{D}{d}\right) - 1.322272\left(\frac{D}{d}\right)^2} \quad (1)$$

We programmed simplified software in C++ under the Microsoft Visual Studio 2019 development environment to automate the calculations and facilitate obtaining the results.

From Equation 1, the original RT values, and using the simple C++ program, we calculate the d data, the errors in millimeters for the set of d values, and the percentage error in the AVR measurement for each original d value.

We used the Statistical Package for the Social Sciences (SPSS), version 25 for Windows (SPSS, Inc., Chicago, IL, USA), to calculate the mean, standard deviation, and summary numbers of the error distributions in millimeters and degrees.

III. RESULTS

Table 2 shows, by different colors, the difference between the original RT d values and the values obtained using Equation 1 to one decimal place.

2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	5.0	5.1	**2º**
2.5	2.6	2.7	2.8	3.0	3.1	3.2	3.3	3.5	3.6	3.7	3.8	4.0	4.1	4.2	4.3	4.5	4.6	4.7	4.8	5.0	5.1	5.2	5.3	5.5	5.6	**4º**
2.7	2.9	3.0	3.1	3.3	3.4	3.5	3.7	3.8	3.9	4.1	4.2	4.3	4.5	4.6	4.8	4.9	5.0	5.2	5.3	5.4	5.6	5.7	5.8	6.0	6.1	**6º**
3.0	3.1	3.3	3.4	3.6	3.7	3.9	4.0	4.1	4.3	4.4	4.6	4.7	4.9	5.0	5.2	5.3	5.5	5.6	5.8	5.9	6.1	6.2	6.4	6.5	6.7	**8º**
3.2	3.4	3.5	3.7	3.9	4.0	4.2	4.4	4.5	4.7	4.8	5.0	5.2	5.3	5.5	5.6	5.8	6.0	6.1	6.3	6.5	6.6	6.8	6.9	7.1	7.3	**10º**
3.5	3.7	3.9	4.0	4.2	4.4	4.6	4.7	4.9	5.1	5.3	5.4	5.6	5.8	6.0	6.1	6.3	6.5	6.7	6.8	7.0	7.2	7.4	7.5	7.7	7.9	**12º**
3.8	4.0	4.2	4.4	4.5	4.7	4.9	5.1	5.3	5.5	5.7	5.9	6.1	6.3	6.4	6.6	6.8	7.0	7.2	7.4	7.6	7.8	8.0	8.2	8.3	8.5	**14º**
4.1	4.3	4.5	4.7	4.9	5.1	5.3	5.5	5.7	5.9	6.1	6.4	6.6	6.8	7.0	7.2	7.4	7.6	7.8	8.0	8.2	8.4	8.6	8.8	9.0	9.2	**16º**
4.4	4.6	4.9	5.1	5.3	5.5	5.7	6.0	6.2	6.4	6.6	6.9	7.1	7.3	7.5	7.7	8.0	8.2	8.4	8.6	8.8	9.1	9.3	9.5	9.7	9.9	**18º**
4.8	5.0	5.2	5.5	5.7	6.0	6.2	6.4	6.7	6.9	7.1	7.4	7.6	7.9	8.1	8.3	8.6	8.8	9.0	9.3	9.5	9.8	10.0	10.2	10.5	10.7	**20º**
5.1	5.4	5.6	5.9	6.1	6.4	6.7	6.9	7.2	7.4	7.7	7.9	8.2	8.4	8.7	9.0	9.2	9.5	9.7	10.0	10.2	10.5	10.8	11.0	11.3	11.5	**22º**
5.5	5.8	6.1	6.3	6.6	6.9	7.2	7.4	7.7	8.0	8.3	8.5	8.8	9.1	9.4	9.6	9.9	10.2	10.5	10.7	11.0	11.3	11.6	11.8	12.1	12.4	**24º**
5.9	6.2	6.5	6.8	7.1	7.4	7.7	8.0	8.3	8.6	8.9	9.2	9.4	9.7	10.0	10.3	10.6	10.9	11.2	11.5	11.8	12.1	12.4	12.7	13.0	13.3	**26º**
6.3	6.6	7.0	7.3	7.6	7.9	8.2	8.5	8.9	9.2	9.5	9.8	10.1	10.4	10.8	11.1	11.4	11.7	12.0	12.3	12.7	13.0	13.3	13.6	13.9	14.2	**28º**
6.8	7.1	7.5	7.8	8.1	8.5	8.8	9.2	9.5	9.8	10.2	10.5	10.9	11.2	11.5	11.9	12.2	12.5	12.9	13.2	13.6	13.9	14.2	14.6	14.9	15.3	**30º**
7.3	7.6	8.0	8.3	8.7	9.1	9.4	9.8	10.2	10.5	10.9	11.3	11.6	12.0	12.3	12.7	13.1	13.4	13.8	14.2	14.5	14.9	15.2	15.6	16.0	16.3	**32º**
7.8	8.2	8.5	8.9	9.3	9.7	10.1	10.5	10.9	11.3	11.6	12.0	12.4	12.8	13.2	13.6	14.0	14.4	14.8	15.1	15.5	15.9	16.3	16.7	17.1	17.5	**34º**
8.3	8.7	9.1	9.5	10.0	10.4	10.8	11.2	11.6	12.0	12.5	12.9	13.3	13.7	14.1	14.5	14.9	15.4	15.8	16.2	16.6	17.0	17.4	17.8	18.3	18.7	**36º**
8.9	9.3	9.8	10.2	10.6	11.1	11.5	12.0	12.4	12.9	13.3	13.7	14.2	14.6	15.1	15.5	16.0	16.4	16.9	17.3	17.7	18.2	18.6	19.1	19.5	20.0	**38º**
9.5	9.9	10.4	10.9	11.4	11.8	12.3	12.8	13.3	13.7	14.2	14.7	15.2	15.6	16.1	16.6	17.0	17.5	18.0	18.5	18.9	19.4	19.9	20.4	20.8	21.3	**40º**
10.1	10.6	11.1	11.6	12.1	12.6	13.1	13.6	14.2	14.7	15.2	15.7	16.2	16.7	17.2	17.7	18.2	18.7	19.2	19.7	20.2	20.7	21.2	21.7	22.2	22.7	**42º**
10.8	11.3	11.9	12.4	12.9	13.5	14.0	14.6	15.1	15.6	16.2	16.7	17.2	17.8	18.3	18.9	19.4	19.9	20.5	21.0	21.6	22.1	22.6	23.2	23.7	24.3	**44º**
11.5	12.1	12.6	13.2	13.8	14.4	14.9	15.5	16.1	16.7	17.2	17.8	18.4	19.0	19.5	20.1	20.7	21.3	21.8	22.4	23.0	23.5	24.1	24.7	25.3	25.8	**46º**
12.2	12.8	13.5	14.1	14.7	15.3	15.9	16.5	17.1	17.7	18.4	19.0	19.6	20.2	20.8	21.4	22.0	22.6	23.2	23.9	24.5	25.1	25.7	26.3	26.9	27.5	**48º**
13.0	13.7	14.3	15.0	15.6	16.3	16.9	17.6	18.2	18.9	19.5	20.2	20.8	21.5	22.1	22.8	23.4	24.1	24.7	25.4	26.0	26.7	27.3	28.0	28.6	29.3	**50º**
13.8	14.5	15.2	15.9	16.6	17.3	18.0	18.7	19.4	20.1	20.8	21.5	22.1	22.8	23.5	24.2	24.9	25.6	26.3	27.0	27.7	28.4	29.1	29.8	30.4	31.1	**52º**
14.7	15.4	16.2	16.9	17.6	18.4	19.1	19.8	20.6	21.3	22.1	22.8	23.5	24.3	25.0	25.7	26.5	27.2	27.9	28.7	29.4	30.1	30.9	31.6	32.3	33.1	**54º**
15.6	16.4	17.2	17.9	18.7	19.5	20.3	21.1	21.8	22.6	23.4	24.2	25.0	25.7	26.5	27.3	28.1	28.9	29.6	30.4	31.2	32.0	32.8	33.5	34.3	35.1	**56º**
16.5	17.4	18.2	19.0	19.8	20.7	21.5	22.3	23.1	24.0	24.8	25.6	26.4	27.3	28.1	28.9	29.7	30.6	31.4	32.2	33.1	33.9	34.7	35.5	36.4	37.2	**58º**
17.5	18.4	19.2	20.1	21.0	21.9	22.7	23.6	24.5	25.4	26.2	27.1	28.0	28.9	29.7	30.6	31.5	32.4	33.2	34.1	35.0	35.9	36.7	37.6	38.5	39.3	**60º**
D20	**D21**	**D22**	**D23**	**D24**	**D25**	**D26**	**D27**	**D28**	**D29**	**D30**	**D31**	**D32**	**D33**	**D34**	**D35**	**D36**	**D37**	**D38**	**D39**	**D40**	**D41**	**D42**	**D43**	**D44**	**D45**	

5.2	5.3	5.4	5.5	5.6	5.7	5.9	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.8	6.9	7.0	7.1	7.2	7.3	7.4	7.5	7.7	7.8	7.9	**2º**
5.7	5.8	5.9	6.1	6.2	6.3	6.4	6.6	6.7	6.8	6.9	7.1	7.2	7.3	7.4	7.6	7.7	7.8	7.9	8.1	8.2	8.3	8.4	8.5	8.7	**4º**
6.2	6.4	6.5	6.7	6.8	6.9	7.1	7.2	7.3	7.5	7.6	7.7	7.9	8.0	8.1	8.3	8.4	8.6	8.7	8.8	9.0	9.1	9.2	9.4	9.5	**6º**
6.8	7.0	7.1	7.3	7.4	7.6	7.7	7.9	8.0	8.2	8.3	8.4	8.6	8.7	8.9	9.0	9.2	9.3	9.5	9.6	9.8	9.9	10.1	10.2	10.4	**8º**
7.4	7.6	7.7	7.9	8.1	8.2	8.4	8.5	8.7	8.9	9.0	9.2	9.4	9.5	9.7	9.8	10.0	10.2	10.3	10.5	10.6	10.8	11.0	11.1	11.3	**10º**
8.1	8.2	8.4	8.6	8.8	8.9	9.1	9.3	9.5	9.6	9.8	10.0	10.2	10.3	10.5	10.7	10.9	11.0	11.2	11.4	11.6	11.7	11.9	12.1	12.3	**12º**
8.7	8.9	9.1	9.3	9.5	9.7	9.9	10.0	10.2	10.4	10.6	10.8	11.0	11.2	11.4	11.6	11.8	11.9	12.1	12.3	12.5	12.7	12.9	13.1	13.3	**14º**
9.4	9.6	9.8	10.0	10.2	10.4	10.7	10.9	11.1	11.3	11.5	11.7	11.9	12.1	12.3	12.5	12.7	12.9	13.1	13.3	13.5	13.7	13.9	14.1	14.3	**16º**
10.2	10.4	10.6	10.8	11.0	11.3	11.5	11.7	11.9	12.2	12.4	12.6	12.8	13.0	13.3	13.5	13.7	13.9	14.1	14.4	14.6	14.8	15.0	15.2	15.5	**18º**
10.9	11.2	11.4	11.7	11.9	12.1	12.4	12.6	12.9	13.1	13.3	13.6	13.8	14.0	14.3	14.5	14.8	15.0	15.2	15.5	15.7	15.9	16.2	16.4	16.7	**20º**
11.8	12.0	12.3	12.5	12.8	13.1	13.3	13.6	13.8	14.1	14.3	14.6	14.8	15.1	15.4	15.6	15.9	16.1	16.4	16.6	16.9	17.2	17.4	17.7	17.9	**22º**
12.7	12.9	13.2	13.5	13.8	14.0	14.3	14.6	14.9	15.1	15.4	15.7	16.0	16.2	16.5	16.8	17.1	17.3	17.6	17.9	18.2	18.4	18.7	19.0	19.3	**24º**
13.6	13.9	14.2	14.5	14.8	15.1	15.3	15.6	15.9	16.2	16.5	16.8	17.1	17.4	17.7	18.0	18.3	18.6	18.9	19.2	19.5	19.8	20.1	20.4	20.7	**26º**
14.6	14.9	15.2	15.5	15.8	16.1	16.5	16.8	17.1	17.4	17.7	18.0	18.4	18.7	19.0	19.3	19.6	19.9	20.3	20.6	20.9	21.2	21.5	21.8	22.2	**28º**
15.6	15.9	16.3	16.6	17.0	17.3	17.6	18.0	18.3	18.6	19.0	19.3	19.7	20.0	20.3	20.7	21.0	21.4	21.7	22.0	22.4	22.7	23.1	23.4	23.7	**30º**
16.7	17.1	17.4	17.8	18.1	18.5	18.9	19.2	19.6	20.0	20.3	20.7	21.1	21.4	21.8	22.1	22.5	22.9	23.2	23.6	24.0	24.3	24.7	25.0	25.4	**32º**
17.9	18.2	18.6	19.0	19.4	19.8	20.2	20.6	21.0	21.4	21.7	22.1	22.5	22.9	23.3	23.7	24.1	24.5	24.9	25.2	25.6	26.0	26.4	26.8	27.2	**34º**
19.1	19.5	19.9	20.3	20.8	21.2	21.6	22.0	22.4	22.8	23.2	23.7	24.1	24.5	24.9	25.3	25.7	26.2	26.6	27.0	27.4	27.8	28.2	28.6	29.1	**36º**
20.4	20.8	21.3	21.7	22.2	22.6	23.1	23.5	23.9	24.4	24.8	25.3	25.7	26.2	26.6	27.1	27.5	27.9	28.4	28.8	29.3	29.7	30.2	30.6	31.0	**38º**
21.8	22.3	22.7	23.2	23.7	24.2	24.6	25.1	25.6	26.0	26.5	27.0	27.5	27.9	28.4	28.9	29.4	29.8	30.3	30.8	31.3	31.7	32.2	32.7	33.1	**40º**
23.2	23.8	24.3	24.8	25.3	25.8	26.3	26.8	27.3	27.8	28.3	28.8	29.3	29.8	30.3	30.8	31.3	31.8	32.3	32.8	33.4	33.9	34.4	34.9	35.4	**42º**
24.8	25.3	25.9	26.4	26.9	27.5	28.0	28.6	29.1	29.6	30.2	30.7	31.3	31.8	32.3	32.9	33.4	34.0	34.5	35.0	35.6	36.1	36.6	37.2	37.7	**44º**
26.4	27.0	27.6	28.1	28.7	29.3	29.9	30.4	31.0	31.6	32.2	32.7	33.3	33.9	34.5	35.0	35.6	36.2	36.8	37.3	37.9	38.5	39.1	39.6	40.2	**46º**
28.1	28.7	29.4	30.0	30.6	31.2	31.8	32.4	33.0	33.6	34.3	34.9	35.5	36.1	36.7	37.3	37.9	38.5	39.1	39.8	40.4	41.0	41.6	42.2	42.8	**48º**
29.9	30.6	31.2	31.9	32.5	33.2	33.8	34.5	35.1	35.8	36.5	37.1	37.8	38.4	39.1	39.7	40.4	41.0	41.7	42.3	43.0	43.6	44.3	44.9	45.6	**50º**
31.8	32.5	33.2	33.9	34.6	35.3	36.0	36.7	37.4	38.1	38.8	39.4	40.1	40.8	41.5	42.2	42.9	43.6	44.3	45.0	45.7	46.4	47.1	47.8	48.4	**52º**
33.8	34.5	35.3	36.0	36.8	37.5	38.2	39.0	39.7	40.4	41.2	41.9	42.6	43.4	44.1	44.8	45.6	46.3	47.0	47.8	48.5	49.2	50.0	50.7	51.5	**54º**
35.9	36.7	37.4	38.2	39.0	39.8	40.6	41.3	42.1	42.9	43.7	44.4	45.2	46.0	46.8	47.6	48.3	49.1	49.9	50.7	51.5	52.2	53.0	53.8	54.6	**56º**
38.0	38.8	39.7	40.5	41.3	42.1	43.0	43.8	44.6	45.4	46.3	47.1	47.9	48.8	49.6	50.4	51.2	52.1	52.9	53.7	54.5	55.4	56.2	57.0	57.8	**58º**
40.2	41.1	42.0	42.8	43.7	44.6	45.5	46.3	47.2	48.1	49.0	49.8	50.7	51.6	52.5	53.3	54.2	55.1	56.0	56.8	57.7	58.6	59.5	60.3	61.2	**60º**
D46	**D47**	**D48**	**D49**	**D50**	**D51**	**D52**	**D53**	**D54**	**D55**	**D56**	**D57**	**D58**	**D59**	**D60**	**D61**	**D62**	**D63**	**D64**	**D65**	**D66**	**D67**	**D68**	**D69**	**D70**	

Table 2. Raimondi's tables with corrected values (rounded to one decimal). The data correspond to the difference between the original RT values and those obtained using Equation 1 to one decimal place. We show the differences by colors: Yellow = difference of 0.1 - 0.2 mm; Orange = difference of 0.3 - 0.4 mm; Red = difference of 0.5 - 0.6 mm; Grey = difference of 0.7 - 0.8 mm; Purple = difference of 0.9 - 1mm; Blue = difference of more than 1 mm. Each column shows a value of D (the width of the vertebral body). The data correspond to the distances d (between the center of the shadow of the pedicle furthest from the lateral side of the vertebral body and the lateral side of the vertebral body, in millimeters). Each pair of values (D, d) corresponds to a value of AVR (axial vertebral rotation) between 2º and 60º.

Table 3 (supplementary material) shows the d values of RT improved without rounding. Table 4 (supplementary material) shows the errors in millimeters for the set of 1530 d values in the RT. The distribution of these errors is Me (mean error) = 0.43 mm, SD (standard deviation) = 0.33 mm, Max (maximum value) = 2.11 mm, Q3 (third quartile) = 0.61 mm, median = 0.35 mm, Q1 (first quartile) = 0.18 mm, and Min (minimum value) = 0. Table 5 (supplementary material) shows the percentage of error in the AVR measurement that each original d value supposes. The distribution of the error due to those errors is Me = 2.57º, SD = 3.8º, Max = 26º, Q3 = 2.53º, median = 1.18º, Q1 = 0.62º, and Min = 0º.

Figure 1 shows how the error in the values of d (distance between the center of the shadow of the pedicle furthest from the lateral side of the vertebral body and this lateral side of the vertebral body) and, therefore, those of AVR varies as a function of the width of the vertebra (D). As these errors are large for small values of D, they decrease as D increases and increase sharply when D is larger than 60 mm. In addition, for small values of D, minor errors in d produce high AVR errors, attenuating as the value of D increases up to D = 42 mm.

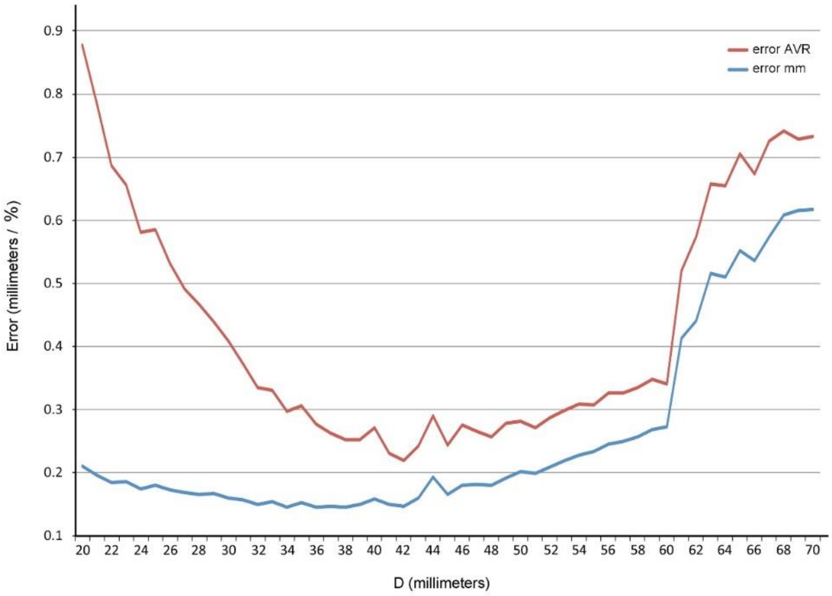

Fig 1: Mean error in millimeters (blue line) and mean percentage error (red line) in the axial vertebral rotation measurement of the distribution of d values (distance between the center of the shadow of the pedicle furthest from the lateral side of the vertebral body and this lateral side of the vertebral body) for each D (vertebral body width) value. The axial vertebral rotation error decreases progressively as the width of the vertebral body (D) increases. From a D of 60 mm, there is a sharp increase in rotational error.

Figure 2 shows how the error percentage in the AVR value is substantial and variable when considering the d values corresponding to AVR = 2º, AVR = 4º and AVR = 6º, decreasing to be very small in the d values corresponding to AVR = 30º and AVR = 44º.

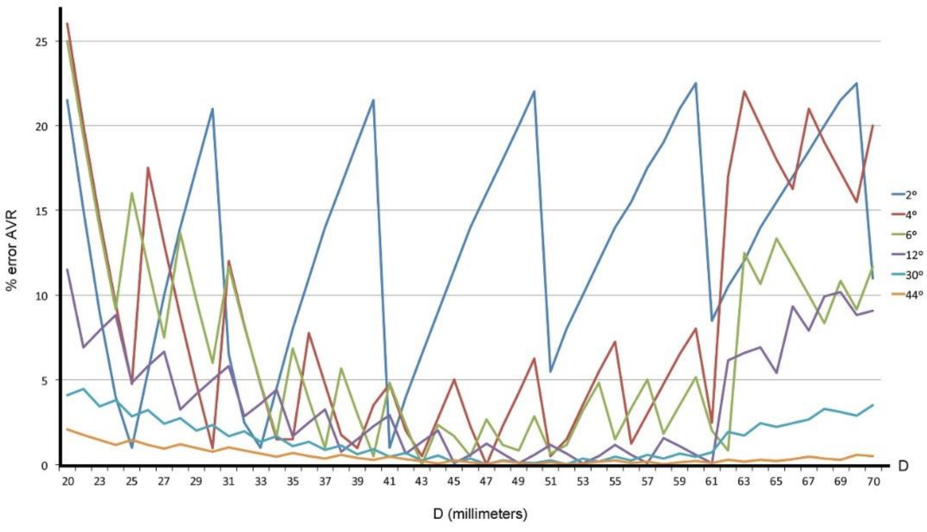

Fig 2: Values percentage error in the axial vertebral rotation of 2º, 4º, 6º, 12º, 30º and 44º from Raimondi's table, for each vertebral body width (D) value due to errors in the distance between the center of the shadow of the pedicle furthest from the lateral side of the vertebral body and this lateral side of the vertebral body (d) values. The axial vertebral rotation percentage error is variable and considerable at the 2º, 4º, and 6º axial vertebral rotation values. On the other hand, it describes more constant and much smaller values for the axial vertebral rotation values corresponding to 30º and 44º.

IV. DISCUSSION

AVR is essential to correctly evaluate, monitor, and treat scoliosis [2,4,5,21,28,29]. For assessing AVR using conventional X-rays films, Raimondi's method stands out for its simplicity, precision, and accuracy [16,24,26]. The data contained in RT were obtained experimentally from thousands of measurements on educational and anatomical spines [13]. In addition, the large amount of information obtained has been simplified to be used practically using a table (RT). Consequently, Raimondi recognizes that the measurements obtained with his method involve systematic errors [13,25].

Advances in computer technology have allowed us to mathematically model the empirical data tabulated in the RT and thus reduce the systematic errors produced in taking AVR measurements [27]. This modeling is embodied in Equation 1, which significantly improves the RT data. Its application results in measures with lower systematic error.

The existence of errors in the values of d can produce a significant error in the determination of AVR (even more than 25% of the actual value) when the measured rotation is slight. The relative importance of this error decreases as the measured rotation becomes larger.

The precision and accuracy of a measuring instrument depend on the purpose of the measurements. On the one hand, and in this sense, the values provided by the original RT method may be adequate for a non-exhaustive general assessment of scoliosis and monitoring the evolution of AVR [12,25]. However, on the other hand, a lack of precision or accuracy measuring AVR may lead to misinterpretation of the course of scoliosis or inadequate therapeutic decisions (conservative or surgical).

Although the systematic errors introduced in the measurements can be minor compared to the actual measurement, it is necessary to consider the error propagation effect. The systematic error of RT combines in a nonlinear way with extrinsic mistakes in the measurement method, such as, for example, the error due to defects or noise in the medical image, the presence of vertebral rotations in planes other than the axial one, vertebral deformations typical of scoliosis or limitations due to the observer.

To our knowledge, Raimondi's is still the state of the art for manual AVR measurement and has not been improved since its publication.

There are some limitations to our study. Firstly, the proposed mathematical method is not an innovation of Raimondi's method but a way to improve its precision and accuracy. Our proposal is limited to correcting the value of the data in RT, so the limitations inherent to the application of this measurement method remain. Secondly, although the data obtained eliminates the intrinsic error of Raimondi's method, the measurements will still contain an error because each pair of data D and d corresponds to an AVR average, which is the same for all vertebrae regardless of their type (e.g., high thoracic or lumbar). Thirdly, we have yet to analyze the final improvement the corrected data can bring when measurements are made in a conventional manual way, employing a comparative study using the original RT. Despite these limitations, the authors consider this innovation worthwhile for clinical practice as it improves the accuracy of measurements obtained with the Raimondi method for assessing AVR.

V. CONCLUSION

We have analyzed and calculated the systematic error in the RT data. The error in the data set is Me = 0.43 mm, SD = 0.33 mm, introducing an error of Me = 2.57º, SD = 3.8º in the AVR measurements. The error in the data is large when the D value is small, decreasing as D increases, and increasing sharply when D is larger than 60 mm. We have obtained values lacking this intrinsic error to replace the classical RT values, allowing Raimondi's method to determine the AVR more accurately than the original RT.

VI. DECLARATION OF CONFLICTING INTERESTS

The authors declare no potential conflicts of interest regarding the research, authorship, and/or publication of this article. The authors received no financial support for this article's research, authorship, and publication. Due to its characteristics, the study does not require ethical approval.

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