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Influence of Footedness on Dynamic Joint Stiffness during the Gait Stance Phase

Tiago Atalaia[1*], João M. C. S. Abrantes[2] and Alexandre Castro-Caldas[3]

[1]Portuguese Red Cross Health School, Avenida de Ceuta, Edifício Urbiceuta, Piso 6, 1300-125 Lisboa, Portugal.
[2]MovLab/CICANT/Lusófona University of Humanities and Technology, Campo Grande 376, 1749-024 Lisboa, Portugal.
[3]Health Sciences Institute, Catholic University of Portugal, Travessa da Palma, 1649-023 Lisboa, Portugal.

Authors' contributions

This work was carried out in collaboration between all authors. Author TA designed the study, performed the literatures searches and statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Author JMCSA designed the study and managed the analyses of the study. Author ACC managed the analysis of the study. All authors read and approved the final manuscript.

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ABSTRACT

Aims: Dynamic joint stiffness (DJS) is used as a joint stability indicator. The objective of the present study is to verify the influence of footedness in ankle joint stability during the gait stance phase.
Study Design: Comparative study.
Place and Duration of Study: MovLab/ CICANT/ Universidade Lusófona de Humanidades e Tecnologias, between November 2013 and June 2014
Methodology: 31 subjects (20 female and 11 male) presenting different footedness (right and left) were assessed. Ten gait stance phase trials (five each side) were recorded using a 3D motion capture system and a force platform. Synchronized ankle sagittal moment of force and angular position were used to calculate DJS for three defined sub-phases of gait stance phase: controlled

**Corresponding author: Email: tatalaia@esscvp.eu, tatalaia.pessoal@gmail.com;*

plantar flexion, controlled dorsiflexion and powered plantar flexion. Mann-Whitney U test was calculated to assess footedness influence on biomechanical variables.
Results: No significant differences were found between dominant and non-dominant limb in different combinations of footedness and gender.
Conclusion: Footedness do not seem to influence DJS and consequent joint stability. Observing the trials per participant, differences can be noted but commonly used statistical approach cannot highlight those differences. Further studies should address ankle frontal plane behaviour or assess differences at the knee and hip joints, as they could present more differences that could be statistically significant.

Keywords: Gait; dynamic joint stiffness; joint stability; footedness.

1. INTRODUCTION

Joint stability can be defined as control of the alignment of the joint segments and its angular position along an intended pathway, within the normal limits of the joint's movement freedom [1-3]. This ability is the sum of the contributions that passive and active joint components make to stability in typical daily living tasks. Dynamic joint stiffness (DJS) is the method usually used to study joint stability, as it serves as a joint stability indicator [1,3]. DJS is defined as the resistance offered by muscles and other joint structures to displacement of joint segments, and as a reaction to the external moment of force [1]. The behaviour of joint moments and angles relations [4-6] can be used to assess DJS. Kinetic-kinematic analysis of DJS allows observations of the spring-like behaviour of the joint and the mechanical energy exchanges [4,6]. In the gait stance phase the typical changes in these variables at the ankle joint sagittal plane follow a simple loop-shape plot as illustrated in Fig. 1 [1,4,5]. Crenna and Frigo [4] divided this loop into three basic sub-phases: the first sub-phase starts at initial contact, with a plantar flexion movement associated with a plantar flexion moment; the second sub-phase begins at load response phase, when a change in the direction of ankle movement towards dorsiflexion paired with a dorsiflexion moment can be observed; the third sub-phase start when both angle and moment decrease, indicating a plantar flexion movement and moment that occurs in preparation for the gait swing phase. Safaeepour and colleagues [6] proposed that these sub-phases could be used to calculate DJS throughout gait stance phase, naming them the controlled plantar flexion (CPF), controlled dorsiflexion (CDF) and powered plantar flexion (PPF) phases respectively.

DJS scores are calculated by computing the slope value of the linear regression line for each of the sub-phases described [6]. Examples of computed regression lines for each sub-phase, in which slope values indicate DJS, are given in Fig. 1.

The DJS score can be used to analyse joint stability; higher DJS scores indicate a stiffer, more stable joint. Several studies have shown that DJS is very consistent across ages [4], others have reported gender differences, with female subjects having lower stiffness scores then male subjects [1,7]. DJS seems to be influenced by gait speed, as studies have shown that it increases with speed [6].

In our review of the literature we found no studies of the relationship between DJS and footedness. Given that footedness is a demonstrable preference for using one foot rather than the other and has an impact on the functional asymmetry of movement [8-13], differences between DJS in the dominant and non-dominant lower limbs should be expected [14]. The lack of evidence on this relationship may be due to the lack of importance attached to footedness by the research study, even though some studies have suggested that footedness is a better predictor of cerebral dominance than handedness, because it is less subject to cultural influences [13,15].

Both self-report questionnaires and observation of performance are routinely used to assess footedness and there is no consensus on which measure is best in spite of a considerable body of evidence [12,15-17]. We used the Lateral Preference Inventory as it has good reliability in the assessment of lateral profile, which comprises handedness, footedness, eyedness and earedness [16].

Gait asymmetries can be consequences of asymmetries in the contribution of left and right limbs to the gait propulsion and control

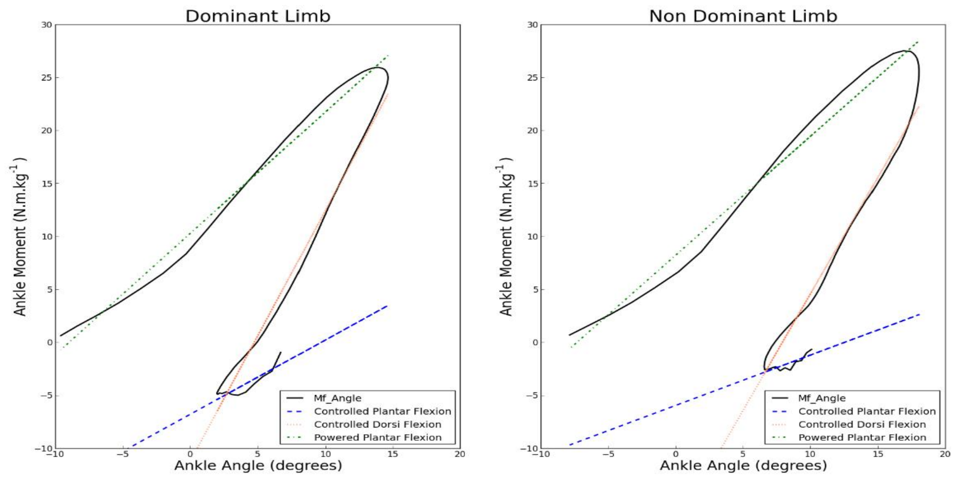

Fig. 1. Example of ankle joint moment-angle plot for the dominant and non-dominant lower limb, selected from the study sample.

phases [18]. So the aim of this study was to investigate the influence of footedness on ankle sagittal plane DJS during the gait stance phase. It was hypothesised that inter-limb differences should be present in the right-footed and left-footed groups. This analysis could be used to make a more objective assessment of footedness, as it relies on use of biomechanical indicators, which would have benefits in injury prevention and rehabilitation settings.

2. METHODOLOGY

2.1 Subjects and Procedures

Subjects were selected by online invitation. Invitations included a description of the purpose of the study and procedures used and subjects provided informed consent in accordance with Helsinki Declaration. Subjects were sent an online version of the Lateral Performance Inventory (LPI) [16] to complete, online questionnaires have proved to be reliable [19], so we chose to use an online version to allow us to increase the sample size. A total of 164 subjects completed the LPI and a sample of 31 of these was selected for laboratory-based performance assessments on the basis of the following criteria: age between 18 and 40 years, with no history of ankle injury or instability, assessed prior to the data collection procedures. We deliberately selected a sample containing as many left-footed subjects as possible. The sample was made up of 20 females (mean age = 23.0 years ± 2.98; mean weight = 60.3±9.8 kg; mean height = 163±6.3 cm) and 11 males (mean age 23.64 years ± 2.25; mean weight = 74.4±11.6 kg; mean height = 176.1±5.1). Footedness distribution was 85% right-footed and 15% left-footed in the female subjects and 72.73% right-footed and 27.27% left-footed in the male subjects. Footedness scores were calculated in accordance with LPI instructions [16].

The experimental procedure involved the re-administration of the LPI prior to the collection of other data; rather than providing verbal responses subjects were asked to perform each task whilst the examiner observed their behaviour. This allowed us to confirm footedness and the other indices of laterality included in the LPI. Biomechanical data were collected at MovLab (Universidade Lusófona de Humanidades e Tecnologias, Lisbon, Portugal). Gait kinematic data were recorded at 200Hz using a 3D motion capture system (Vicon®Motion Capture MX System, Oxford UK), composed of 9 MX (7*1.3Gb; 2*2.0Gb) which were connected to the MXUltranet control hardware and used to track the motion of the 41 spherical reflexive markers (9.5mm diameter) that make up the PlugInGait-Full Body model. Anthropometric data, needed for the PlugInGait-Full Body model, were collected using the SECA 764 scale and Siber Hegner anthropometric measurement instruments. Synchronized kinetic data were recorded at 1000Hz using a force platform (AMTI BP400600-2000, USA) connected to a strain gauge amplifier (AMTI MSA-6 MiniAmp). The subjects were instructed to walk barefoot along a 7m path at their normal speed. The path was in the form of a loop so that subjects could complete one walk trial at a stable speed, without stopping. Subjects were instructed to maintain a constant walking speed and avoid targeting the force platform. A total of 10 sets of gait stance phase data per subject were selected for analysis (5 each side) from the valid sets (those in which all the stance sub-phases were present).

2.2 Data Processing

Kinematic and kinetic data acquisition and processing was done using Vicon® Nexus software (version 1.7.1), with a Woltring filter routine [20,21]. Ankle moment of force (normalized to body weight) and joint angle were normalized to percentages of the gait stance phase to allow inter-limb comparisons. The moment-angle plot for each stance phase in all participants was calculated using the method described by Safaeepour and colleagues [6]: the loop is divided into three sub-phases, CPF, CDF and PPF, as described above. Ankle joint DJS in each sub-phase was calculated using the standard formula DJS=dM/dθ, where M is the ankle moment of force and θ is the ankle sagittal angle [1,4,6]. Least-squares regression models were used to calculate regression lines for each of the sub-phases6. The DJS calculation was performed for every trial of every participant. Mean DJS values for each participant were used in the statistical analysis. The Kolmogorov-Smirnov test showed that scores were not normally distributed so the Mann-Whitney U test was used to assess the influence of footedness on DJS scores. Statistical analysis was carried out using the Statistical Package for Social Sciences software (SPSS version 20, IBM, USA).

3. RESULTS AND DISCUSSION

Table 1 shows the regression fit given by the coefficient of determination (R2) for each of the regression lines used for DJS calculation. The data are grouped according to gait stance sub-phase and dominant foot. On the dominant side mean values of DJS in each sub-phase were CPF: 0.46±0.27 range 0.07 to 1.22; CDF: 1,43±0.44, range 0.82 to 2.56; PPF: 1.01±0.27 range 0.59 to 1.77. On the non-dominant side mean DJS values were CPF: 0.50±0.32, range 0 to 1.72; CDF: 1.43±0.40 range 0.82 to 2,34; PPF: 1.06±0.26, range from 0.56 to 1.48. On the dominant side mean values of R2 in each sub-phase were CPF: 0.73±0.24, range 0.03 to 0.95; CDF: 0.91±0.06 range 0.79 to 0.98; PPF: 0.97±0.04 range 0.80 to 1.00. On the non-dominant side mean R2 values were CPF: 0.73±0.22, range 0.07 to 0.97; CDF: 0.91±0.07 range 0.64 to 0.98; PPF: 0.97±0.04, range from 0.84 to 1.00.

Separate analyses of all three sub-phases were carried out for the dominant and non-dominant feet and for each gender, as there are reported to be gender differences in DJS [7]. Results of the Kolmogorov-Smirnov test indicated that the data were not normally distributed so we used the Mann-Whitney U test to assess the influence of footedness on DJS. Data were grouped according to footedness and gender: female and male right-footed groups and female and male left-footed groups. The results of the Mann-Whitney U tests are presented in Tables 2 and 3.

The Mann Whitney U test indicated that in male and female right-footed subjects DJS was similar on the dominant and non-dominant sides, and in all the sub-phases, suggesting that there was no influence of footedness on joint stability at any point in the gait stance phase.

Table 3 shows that similar results were found for the left-footed group.

Gait is often assumed to be symmetrical in the lower limbs in order to facilitate gait analysis. Asymmetry is considered pathological [18], but some asymmetry may be the expression of a natural functional difference between the lower limbs [18], possibly related to footedness. This led us to assess lower limb dominance differences in joint stability, operationalised as DJS, during the gait stance phase. DJS values in the CPF were lower than in the other sub-phases, with the regression lines also showing a lower value for R2. Other studies have reported similar differences between the sub-phases and attributed them to the brevity of the CPF sub-phase and the sampling rate used (100 Hz) [6]. In our study, we used a higher sampling rate (200 Hz) which may explain why we obtained higher DJS scores in the CPF sub-phase than. safaeepour and colleagues (for gait at normal speed) although they were still lower than in the other sub-phases and were associated with lower R2 scores [6]. We found similar DJS and R2 values in the CDF and PPF sub-phases to those reported in other studies [4,6]. Our data provide no evidence to suggest that footedness influences lower limb DJS and no evidence for gender- or dominance-related differences in DJS.

Table 1. Individual and sample mean scores for DJS and coefficient of regression (R2) grouped according to gait sub-phase

	CPF						CDF						PPF					
	Dominant			Non-Dominant			Dominant			Non-Dominant			Dominant			Non-Dominant		
Partici-pants	***Mean DJS***	***Mean R^2***	***St Dev***	***Mean DJS***	***Mean R^2***	***St Dev***	***Mean DJS***	***Mean R^2***	***St Dev***	***Mean DJS***	***Mean R^2***	***St Dev***	***Mean DJS***	***Mean R^2***	***St Dev***	***Mean DJS***	***Mean R^2***	***St Dev***
P01	0,85	0,92	0,00	0,61	0,93	0,08	1,95	0,96	0,05	1,88	0,92	0,06	1,19	0,99	0,03	1,15	0,99	0,02
P02	0,41	0,76	0,00	0,74	0,80	0,12	1,93	0,98	0,04	2,32	0,97	0,05	1,11	0,97	0,03	1,20	0,99	0,02
P03	0,17	0,52	0,02	0,18	0,56	0,06	1,24	0,97	0,03	0,99	0,95	0,02	0,69	0,97	0,02	0,83	0,99	0,02
P04	0,42	0,90	0,00	0,34	0,62	0,11	1,75	0,81	0,10	1,54	0,77	0,10	1,12	0,98	0,04	1,48	0,88	0,06
P05	0,27	0,57	0,04	0,38	0,77	0,08	1,34	0,90	0,07	1,21	0,94	0,04	0,73	1,00	0,01	0,71	0,91	0,03
P06	0,37	0,75	0,01	0,45	0,76	0,10	1,01	0,93	0,03	1,03	0,91	0,04	0,70	0,97	0,03	0,85	0,99	0,01
P07	0,44	0,90	0,00	0,70	0,89	0,11	0,93	0,93	0,03	1,62	0,92	0,05	0,73	0,99	0,02	1,29	0,99	0,04
P08	0,55	0,87	0,00	0,32	0,64	0,08	1,33	0,91	0,05	1,96	0,87	0,09	0,99	0,99	0,03	1,03	0,98	0,03
P09	0,65	0,80	0,02	0,45	0,92	0,04	1,61	0,97	0,03	1,96	0,89	0,08	1,01	0,98	0,03	1,33	0,99	0,02
P10	1,22	0,93	0,00	1,72	0,89	0,26	2,56	0,94	0,08	2,34	0,96	0,06	1,26	0,97	0,04	1,23	0,99	0,02
P11	0,31	0,82	0,00	0,40	0,81	0,07	0,94	0,92	0,03	1,31	0,92	0,05	1,07	0,97	0,05	1,01	0,98	0,03
P12	0,32	0,66	0,01	0,22	0,44	0,08	2,07	0,88	0,10	1,61	0,88	0,07	1,20	0,99	0,02	1,37	0,99	0,02
P13	0,16	0,48	0,09	0,33	0,83	0,06	1,23	0,94	0,03	1,19	0,96	0,03	1,21	1,00	0,02	1,04	0,99	0,02
P14	0,26	0,86	0,00	0,00	0,18	0,08	1,16	0,97	0,02	1,04	0,97	0,02	0,77	0,97	0,03	0,86	0,98	0,03
P15	0,11	0,25	0,26	0,11	0,28	0,07	1,54	0,95	0,04	0,86	0,92	0,03	0,87	0,94	0,05	0,96	0,98	0,04
P16	0,25	0,25	0,42	0,67	0,73	0,18	1,21	0,89	0,05	1,50	0,87	0,07	1,44	0,99	0,03	1,43	0,99	0,04
P17	0,75	0,92	0,05	0,38	0,89	0,04	0,97	0,96	0,02	0,92	0,98	0,02	0,59	0,99	0,01	0,56	0,98	0,01
P18	1,07	0,91	0,00	0,76	0,76	0,14	2,36	0,96	0,06	1,91	0,97	0,04	1,11	1,00	0,02	1,19	0,98	0,03
P19	0,57	0,92	0,00	0,74	0,97	0,06	1,64	0,91	0,06	1,48	0,93	0,05	1,14	0,97	0,04	1,18	0,98	0,04
P20	0,62	0,93	0,00	0,60	0,86	0,12	1,09	0,92	0,04	1,02	0,85	0,05	0,83	0,97	0,03	1,06	0,94	0,04
P21	0,67	0,89	0,00	0,45	0,79	0,09	1,06	0,94	0,03	1,29	0,92	0,05	1,23	0,80	0,02	1,07	0,99	0,02
P22	0,42	0,70	0,02	0,59	0,86	0,10	1,01	0,83	0,06	1,06	0,84	0,06	0,81	0,99	0,02	0,84	0,99	0,02
P23	0,50	0,88	0,00	0,29	0,83	0,05	1,49	0,96	0,04	1,40	0,96	0,04	1,34	0,99	0,04	1,48	0,99	0,03
P24	0,44	0,57	0,12	0,55	0,57	0,20	1,36	0,81	0,08	1,33	0,64	0,13	1,04	0,99	0,02	1,05	0,88	0,04
P25	0,07	0,39	0,34	0,23	0,60	0,06	1,56	0,83	0,09	1,48	0,93	0,05	1,06	0,99	0,02	1,15	1,00	0,02
P26	0,46	0,74	0,06	0,78	0,88	0,16	1,28	0,96	0,04	1,31	0,97	0,03	0,59	0,83	0,03	0,57	0,84	0,03
P27	0,24	0,95	0,00	0,59	0,97	0,06	0,82	0,85	0,04	0,82	0,93	0,03	0,73	0,98	0,03	0,73	1,00	0,01
P28	0,60	0,93	0,01	0,46	0,84	0,11	1,46	0,83	0,08	1,60	0,87	0,08	1,24	0,98	0,04	1,21	0,99	0,03
P29	0,36	0,81	0,00	0,95	0,92	0,12	1,07	0,95	0,03	1,59	0,97	0,04	0,85	0,99	0,02	0,80	0,96	0,02
P30	0,08	0,03	0,80	0,19	0,07	0,40	2,10	0,79	0,13	1,73	0,84	0,10	1,77	0,99	0,05	1,46	0,92	0,05
P31	0,59	0,73	0,08	0,49	0,74	0,15	1,35	0,95	0,04	1,10	0,93	0,04	0,90	0,97	0,03	0,90	0,94	0,03
Mean	**0,46**	**0,73**		**0,50**	**0,73**		**1,43**	**0,91**		**1,43**	**0,91**		**1,01**	**0,97**		**1,06**	**0,97**	
StDev	0,27	0,24		0,32	0,22		0,44	0,06		0,40	0,07		0,27	0,04		0,26	0,04	

Table 2. Mann-Whitney U test for the right-footed group. Analysis by gender

			Ranks				
		Right-Footed Female			**Right-Footed Male**		
	Dominance	**N**	**Mean rank**	**Sum of ranks**	**N**	**Mean rank**	**Sum of ranks**
CPF	*Dominant*	17	17,71	301,00	8	6,25	50,00
	Non-dominant	17	17,29	294,00	8	10,75	86,00
	Total	34			16		
CDF	*Dominant*	17	18,06	307,00	8	7,38	59,00
	Non-dominant	17	16,94	288,00	8	9,63	77,00
	Total	34			16		
PPF	*Dominant*	17	15,71	267,00	8	7,88	63,00
	Non-dominant	17	19,29	328,00	8	9,13	73,00
	Total	34			16		

			Test statistics			
	Female			**Male**		
	CPF	**CDF**	**PPF**	**CPF**	**CDF**	**PPF**
Mann-Whitney U	141,000	135,000	114,000	14,000	23,000	27,000
Wilcoxon W	294,000	288,000	267,000	50,000	59,000	63,000
Z	-0,121	-0,327	-1,051	-1,890	-0,945	-0,525
Asymp. Sig. (2-taliled)	0,904	0,744	0,293	0,059	0,345	0,600
Exact Sig. [2*(1-Tailed Sig.)]	0,919[a]	0,760[a]	0,306[a]	0,065[a]	0,382[a]	0,645[a]

a. Not corrected for ties

Table 3. Mann-Whitney U test for the left-footed group. Analysis by gender

Ranks							
		Left-Footed Female			Left-Footed Male		
	Dominance	**N**	**Mean rank**	**Sum of ranks**	**N**	**Mean rank**	**Sum of ranks**
CPF	*Dominant*	3	4,33	13,00	3	3,00	9,00
	Non-dominant	3	2,67	8,00	3	4,00	12,00
	Total	6			6		
CDF	*Dominant*	3	3,67	11,00	3	4,33	13,00
	Non-dominant	3	3,33	10,00	3	2,67	8,00
	Total	6			6		
PPF	*Dominant*	3	4,00	12,00	3	3,67	11,00
	Non-dominant	3	3,00	9,00	3	3,33	10,00
	Total	6			6		

Test statistics						
	Female			**Male**		
	CPF	**CDF**	**PPF**	**CPF**	**CDF**	**PPF**
Mann-Whitney U	2,000	4,000	3,000	3,000	2,000	4,000
Wilcoxon W	8,000	10,000	9,000	9,000	8,000	10,000
Z	-1,091	-0,218	-0,655	-0,655	-1,091	-0,218
Asymp. Sig. (2-taliled)	0,275	0,827	0,513	0,513	0,275	0,827
Exact Sig. [2*(1-Tailed Sig.)]	0,400[a]	1,000[a]	0,700[a]	0,700[a]	0,400[a]	1,000[a]

a. Not corrected for ties

Joint stability during the gait stance phase seems to be similar in the dominant and non-dominant limbs, DJS scores were similar in left and right lower limbs. We predicted that there would be dominance-related gait asymmetries reflecting the normal functional asymmetries present in any human movement [18]. The moment-angle plots of individual subjects, such as that shown Fig. 1 show small differences between sides but no consistent difference was detectable at group level using statistical tests. Some authors have speculated about the existence of inter-limb differences, including differences related to footedness, but it is difficult to find evidence of such differences using common movement time-dependent descriptive data [4,6,14,18]. In this study we used kinematic-kinetic analysis to investigate potential inter-limb differences in joint stability; we expected to detect effects of footedness on dynamic ankle sagittal plane behaviour during the gait stance phase, as suggested by other studies [1,4,6]. Even using this approach we failed to find evidence for the influence of footedness on lower limb stability in the gait stance phase. These findings are relevant to injury prevention and rehabilitation as it is assumed that there are muscle imbalances between dominant and non-dominant lower limbs [22,23], perhaps large enough to render use of the contralateral limb for strength comparison questionable [24]. Taken together our data and previous data suggest that gait alone is not suitable as a substrate for assessing the influence of footedness on human movement, as its time course and energetic demands do lend themselves to the demonstration of inter-limb differences.

4. CONCLUSION

Footedness does not appear to influence ankle joint sagittal DJS scores during the gait stance phase. This indicates that joint stability is similar in the dominant and non-dominant limbs. Sagittal ankle joint stability during gait stance cannot be used as an indicator of footedness. The assessment of footedness and laterality differences will require the use of other dynamic analysis tools as any laterality differences appear to be small and are not detected using common statistical tests. Further studies could assess ankle frontal plane behaviour or dominance differences in joint stability at the knee and hip joints, as dominance effects may be detectable in more proximal joint behavior.

CONSENT

All authors declare that written informed consent was obtained from the patient (or other approved parties) for publication of this case report and accompanying images.

ETHICAL APPROVAL

All authors hereby declare that all procedures have been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. The present study was approved by the ethical board of the Escola Superior de Saúde da Cruz Vermelha Portuguesa.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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