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Optimising rigid ankle foot orthoses design: A quantitative evaluation of trimlines on stiffness

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ABSTRACT

Ankle-foot orthoses (AFOs) are of important in the management of gait deformities in most neurological conditions through stabilising and supporting the ankle and foot. Despite its importance, there is a lack of knowledge about how some design parameters, particularly trimline geometry, affect AFO stiffness. This study employs a parametric finite element (FE) model to quantify the impact of trimline design on rigidity to improve standardisation of AFO prescription manufacture, and quality control. A parametric model was developed to systematically modify trimline placement and analyse its effect on AFO stiffness. A dorsiflexion moment of 30 Nm was employed to simulate loading conditions, with experimentally determined material properties of polypropylene. The parametric model was developed and validated against experimental results. Trimline positions were manipulated systematically by 1 mm in the proximal and 10 mm in the distal direction of ankle to investigate their impact on stiffness. Thickness, loading, and constraints were controlled for in the analysis. The results of this study verify that the model accurately predicts ankle dorsiflexion, and there are small discrepancies between calculation and experiment. Having more than five transverse plates proximal to the footplate and distal to the ankle does not significantly impact stiffness. Furthermore, trimline position has significant effect in AFO rigidity, that even small changes affect stiffness. Change in trimline posterior to the ankle produced a linear decrease in stiffness, while trimline adjustments distal to the ankle had a nonlinear effect. These findings emphasise the importance of precise prescription and quality control of trimlines to optimise the AFO function.

1. Introduction

Ankle-foot orthoses (AFOs) play a critical role in managing gait abnormalities in numerous clinical conditions [1]. These devices work by providing support and stability to the foot and ankle joints, thereby improving mobility and function in daily activities [2]. These conditions include cerebral palsy, stroke and other neurological conditions that affect daily life activities and walking ability [3–5]. AFOs are also prescribed to promote muscle stretching and to prevent plantar flexion contractures which is a common complication for people with neurological disorders [6–8].

Rigidity is an important factor for the effectiveness of AFOs [1,2,9]. Insufficient rigidity can lead to numerous consequences for different clinical conditions, including pain, instability, and increased risk of falling [10–14]. Achieving optimal AFO performance relies heavily on achieving the right balance between rigidity, and weight [10].

Although the importance of rigidity is recognised in the literature, there is a critical gap in our understanding on how specific parameters affect the stiffness of AFO and its effectiveness [15,16]. As a result, prescribing clinicians and manufacturers tend to rely heavily on established practices without reliable evidence to guide the design of effective structures [17]. A key parameter that remains poorly understood with regards to its effect on rigidity is the design of trimlines [16].

The rigidity of AFO to dorsiflexion was measured by bending the plastic AFOs using experimental technique [18,19]. The resistance to dorsiflexion decreased in all plastic AFOs as the posterior upright width was reduced. However, since this study was purely experimental, a full parametric analysis was not conducted. To help address this gap in

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knowledge [16], this study developed a parametric finite element (FE) model to quantify the effect of trimline design on AFO stiffness. This approach supports prioritising adequate rigidity to address biomechanical deficits while minimising weight for improved user comfort. A clearer understanding of these relationships will contribute to standardisation and better inform the prescription and manufacturing of AFOs.

2. Methodology

2.1. Model development

The geometry of the reference AFO was captured using a high-precision HandySCAN BLACK™Elite 3D scanner (Creaform). The acquired data was then imported into Solidworks® 2023 (Solidworks, Waltham, Massachusetts) for geometry development. The surface of the AFO model was developed using surface tabs of the Solidworks. The model assumed a uniform thickness matching the reference AFO and employed a fixed footplate in AFO stiffness.

2.2. Parametric geometry design

To isolate and analyse the effect of trimline placement (projection on sagittal plane) on AFO stiffness, a parametric geometry of AFO was developed that enabled adapting the shape end extent of the trimlines. In parametric model, the AFO geometry was represented using a series of transverse planes parallel to the foot plate (Fig. 1.a). These planes were used in Solidworks® to define the geometry of AFO on each cross-section. Partial-elliptical geometries were employed to produce AFO geometry on each cross-section (Fig. 1.b).

The geometry of the AFO proximal to the ankle was represented by landmarks with the relative maximum and minimum radii on AFO, which in this case comprised of five planes (Fig. 1.a). More specifically, planes parallel to the footplates are created where the radii of AFO start to ascend or to descend to make sketches of AFO cross-sections using partial ellipses. The geometry of the AFO, distal to the ankle, was investigated by increasing the number of planes in presenting the geometry and assessing the predicted stiffness convergence.

The model development involved extracting key geometrical parameters from a reference AFO. These parameters included the maximum distance of medial and lateral side of AFO as one of the ellipse's diameters, the projection of medial and lateral trimlines on sagittal plane as the two end of partial ellipse, on both distal and proximal sides relative to the ankle joint. Additionally, the projection of back of the AFO on sagittal plane, which is assumed to correspond to the point of largest radius of the partial-ellipse shape, was included as the

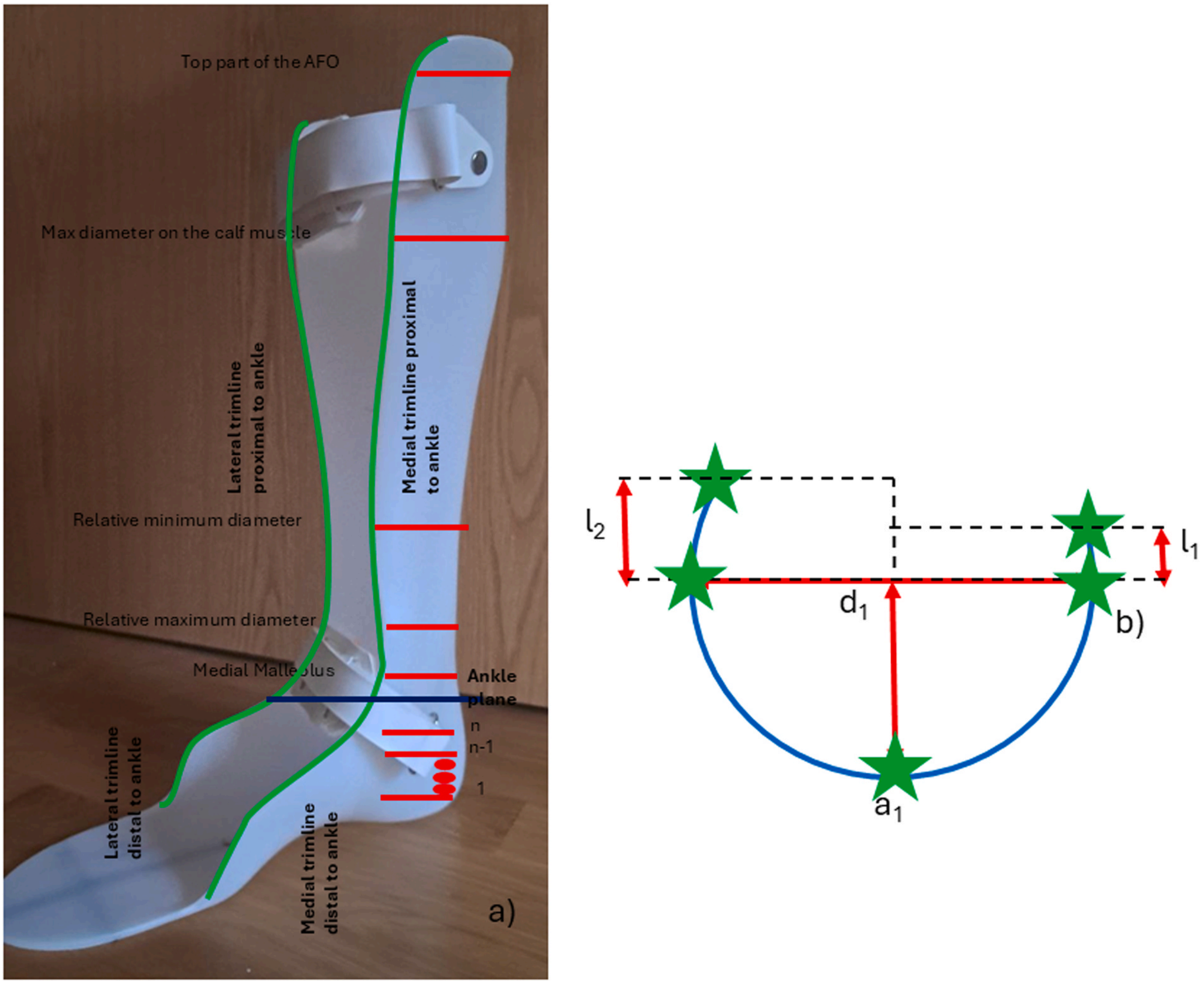

Fig. 1. a) Cross-sections defined proximal and distal to the ankle plane. Proximally, cross-sections are positioned based on the geometric requirements of the actual AFO, considering locations of relative minimum and maximum diameters. Distally, cross-sections extend from 10 mm above the footplate to the ankle plane, with multiple configurations analysed to identify the convergence point, where increasing the number of cross-sections no longer influences AFO stiffness; b) Schematic representation of the AFO cross-section in the parametric model. The cross-sectional area is determined by the maximum diameter of the AFO, while the perpendicular diameter is defined considering the radius as the projection of the centre of the ellipse to the back of the AFO, on sagittal plane.

other parameter to keep correspondence between the original and simplified AFOs. The centre of the ellipse was defined based on the crossing of the short and long diameters of the ellipse (Fig. 1.b). This model allowed for systematic modification of the trimline distance relative to the ankle frontal plane.

Models with varying numbers of planes distal to the ankle were examined to identify the convergence point, where further increasing the number of cross-sections no longer affects AFO stiffness. Four, five, and six transverse planes distal to the ankle plane and proximal to the foot plate. The footplate geometry was accurately represented the reference model's footplate.

A dorsiflexion moment of 30 Nm was applied at the attachment points of the proximal strap. The reference AFO material, polypropylene, was characterised experimentally before to determine its mechanical properties [16]. The model incorporated these properties, simulating linearly elastic perfectly plastic (LEPP) behaviour. The material properties that were utilised: Young's modulus of 5866 MPa, and Yield stress of 521.5 MPa.

2.3. Validation

As outlined in previous research [16], dorsiflexion torque of 30 Nm was applied in measuring the flexion of an ankle-foot orthosis. The stiffness was measured using a torsion device. During testing, the shank was rotated at 1 degree/min around the ankle joint while the reaction moment at the support base was recorded at 100 Hz. Loading was terminated when dorsiflexion torque became equal to 30 Nm. The stiffness was calculated as the applied moment divided by the maximum flexion angle. Each test was repeated 3 times, and their average was used as the final measurement of equivalent stiffness.

2.4. Parametric analysis of trimlines

The parametric model was utilised to analyse how design modifications affect AFO stiffness, proximal and distal to the ankle. The trimlines were systematically adjusted by incrementally reducing the projection of the trimlines on the sagittal plane projection on the medial and lateral sides by 1 mm, proximal to the ankle. Furthermore, the projection was reduced by 10 mm on both medial and lateral sides distal to the ankle. AFO thickness, applied load, and constraints remained consistent with the reference model. The impact of these modifications on AFO stiffness was then evaluated.

3. Results

The model's accuracy in predicting dorsiflexion at the ankle joint varied depending on the design details. Increasing the number of plates distal to the ankle and proximal to the foot plate more than 5, does not change the stiffness of the AFO for more than 1 %.

The dorsiflexion of parametric model of AFO with 5 transverse planes distal to the ankle and proximal to the foot plate, showed 4.75°, with 6.38 Nm/degree stiffness. The dorsiflexed angle of the AFO in the experiment showed 4.70°, which shows 6.45 Nm/degree stiffness to dorsiflexion. The model showed 1 % difference compared to the experimental results.

3.1. The effect of trimlines proximal to the ankle

A linear relationship was observed between the reduction in minimum trimline distance to the ankle joint frontal plane and AFO stiffness, with the structures becoming significantly less stiff when the trimline was pushed in the posterior direction (Fig. 2). Moving the medial trimline in the posterior direction by as little as one mm of the medial side, causes 0.156 Nm/degree decrease in the stiffness Moving the lateral trimline in the posterior direction by as little as one mm, causes 0.116 decrease in the stiffness Moving the medial trimline in the posterior direction by as little as one mm decreased AFO stiffness by 6 % relative to the reference geometry (Table 1). Similarly, one mm movement of the lateral trimline in the posterior direction led to a 3 % decrease in stiffness relative to the reference geometry.

3.2. The effect of trimlines distal to the ankle

On both medial and lateral sides, distal to the ankle, reducing the trimline projection (i.e., moving the trimline posteriorly) resulted in a decrease in AFO stiffness. However, unlike the trimline proximal to the ankle, the relationship between the reduction of the trimline projection on the sagittal plane distal to the ankle and stiffness is not linear (Fig. 2).

Moving the lateral trimline distal to the ankle joint in the posterior direction resulted in a decrease in stiffness. Moving the lateral trimline distal to the ankle joint in posterior direction by 50 mm only caused a 20 % decrease in AFO stiffness compared against the reference stiffness. However, beyond this point, the effect became significantly more pronounced as the trimline approached the ankle plane. Moving the lateral trimline distal to the ankle joint in posterior direction by 90 mm caused a 160 % decrease in AFO stiffness compared against the reference stiffness. Moreover, a 600 % reduction in stiffness was shown after moving posterior to the ankle by 100 mm, due to buckling of the entire structure (Table 2).

4. Discussion

The results presented here show that semi-ellipses in parallel surfaces can represent the AFOs stiffness under dorsiflexion. However, we should consider that there is a minimum number of transverse planes that are needed in parametric geometry to represent an accurate

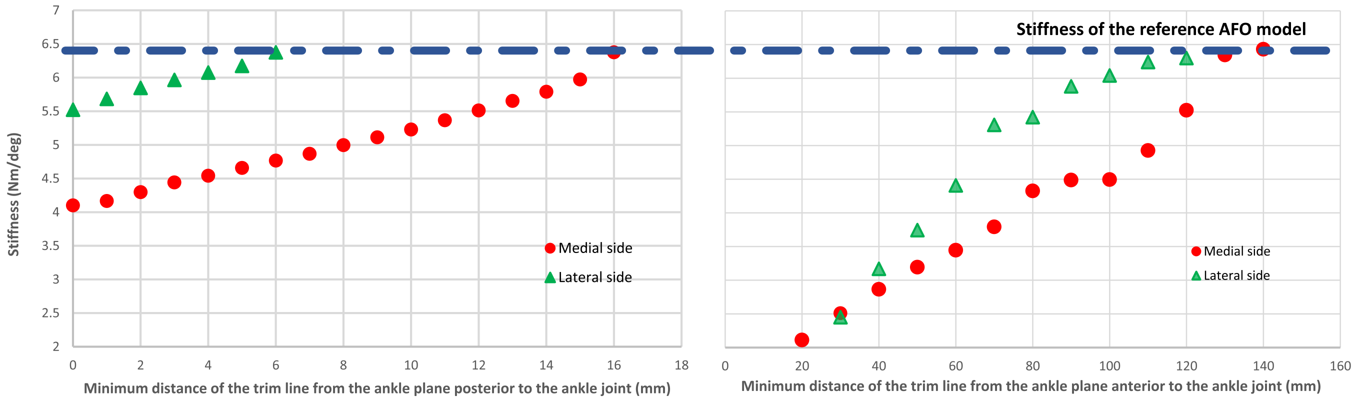

Fig. 2. Change in the stiffness of the AFO in 30 Nm/degree dorsiflexion, by moving the medial and lateral trimlines posterior, proximal and distal to the ankle plane.

Table 1

Change in the stiffness of the AFO in 30 Nm/degree dorsiflexion, by moving the medial and lateral trimlines posterior, proximal to the ankle plane.

Scenarios		**Results – Medial side**			**Results – Lateral side**		
	Minimum distance from the Ankle plane (mm)	**Flexion (degree)**	**Stiffness (Nm/degree)**	**Relative decrease in stiffness to reference (%)**	**Flexion (degree)**	**Stiffness (Nm/degree)**	**Relative decrease in stiffness to reference (%)**
Referenced model		6.38	6.38	0 %	6.38	6.38	0 %
Trimline distance from the ankle plane **proximal to the ankle joint**	15	5.97	5.97	6 %	-	-	-
	14	5.79	5.79	9 %	-	-	-
	13	5.65	5.65	11 %	-	-	-
	12	5.51	5.51	14 %	-	-	-
	11	5.37	5.37	16 %	-	-	-
	10	5.23	5.23	18 %	-	-	-
	9	5.11	5.11	20 %	-	-	-
	8	5.00	5.00	22 %	-	-	-
	7	4.87	4.87	24 %	-	-	-
	6	4.77	4.77	25 %	-	-	-
	5	4.66	4.66	27 %	4.91	6.17	3 %
	4	4.54	4.54	29 %	4.99	6.08	5 %
	3	4.44	4.44	30 %	5.08	5.97	6 %
	2	4.30	4.30	33 %	5.18	5.85	8 %
	1	4.17	4.17	35 %	5.33	5.68	11 %
	0	4.10	4.10	36 %	5.49	5.52	13 %

Table 2

Change in the stiffness of the AFO in 30 Nm/degree dorsiflexion, by moving the medial and lateral trimlines posterior, distal to the ankle plane.

Scenarios		**Results – Medial side**			**Results – Lateral side**		
	Minimum distance from the Ankle plane (mm)	**Flexion (degree)**	**Stiffness (Nm/degree)**	**Relative decrease in stiffness to reference (%)**	**Flexion (degree)**	**Stiffness (Nm/degree)**	**Relative decrease in stiffness to reference (%)**
Referenced model		4.75	6.38	0 %	4.75	6.38	0 %
Trimline distance from the ankle plane **distal to the ankle joint**	140	4.71	6.43	1 %			
	130	4.78	6.35	0 %			
	120	5.49	5.52	13 %	4.81	6.30	1 %
	110	6.15	4.93	23 %	4.86	6.24	2 %
	100	6.74	4.49	30 %	5.02	6.04	5 %
	90	6.75	4.49	30 %	5.15	5.88	8 %
	80	7.01	4.33	32 %	5.59	5.42	15 %
	70	7.99	3.79	41 %	5.71	5.31	17 %
	60	8.79	3.45	46 %	6.87	4.41	31 %
	50	9.49	3.19	50 %	8.09	3.74	41 %
	40	10.58	2.86	55 %	9.56	3.17	50 %
	30	12.07	2.51	61 %	12.36	2.45	62 %
	20	14.35	2.11	67 %	33.24	0.91	86 %

dorsiflexion, which adding one more plane distal to the ankle, did not change the AFO stiffness in dorsiflexion.

Our parametric analysis shows the impact of trimlines and reveals a significant effect of trimlines on the rigidity of the AFO. This finding offers moving in the trimline cut as little as one millimetre will lead to 3 % and 6 % change in the rigidity of the AFO on lateral and medial sides respectively, posterior to the ankle. This shows the significance of detailed prescription and quality control on the trimline cuts based on required rigidity. The results show a linear effect of trimline placement on AFO stiffness, proximal to the ankle joint (i.e., trimlines between ankle joint and knee joint) in rigid AFOs.

The influence of trimline geometry on AFO stiffness has been explored in the past by simulating the geometry of custom-made AFOs [20]. The trimlines were defined from geometrical landmarks, which is different to normal clinical practice used by orthotic technicians. Moreover, the initial AFO model was derived from scans of the leg and not the physical AFO. Hence, the discrepancies between the leg's original shape and the AFO were not considered in the analysis. Their results [20] were consistent with our initial investigation, showing that variations in heel constraints affect AFO stiffness and confirmed the importance of trimlines on AFO's stiffness.

Our findings, using a finite element model are also in-line with Sumiya et al. [19] work who took an experimental approach using physical AFOs. However, results from our study offer a more detailed description of the effects on the medial and lateral sides distinctively. Future research is needed with physical AFOs and an experimental approach to validate these findings [19,21,22]. By comprehensively analysing these factors, we can develop evidence-based guidelines for AFO design, optimising dorsiflexion assist.

Conversely, trimlines distal to the ankle joint have a nonlinear effect on stiffness in the rigid AFO. Interestingly, for the trimline distal to the ankle joint, there appears to be a point beyond, 20 mm anterior to the ankle, which further posterior trimlines causes bulging and instability of the system in the analysis. Future research should investigate the influence of these parameters in physical AFOs to validate these in silico findings.

The findings on distal trimlines to the ankle plane showed a clear difference between medial and lateral sides. A substantial decrease in stiffness was observed on reducing the projection of the medial trimlines on the sagittal plane, particularly beyond the arch point. This can show a critical role for the medial arch area in maintaining AFO's rigidity. Trimlines posterior to the arch point on the medial side, should be considered in the prescription and quality control based on the required stiffness. Conversely, the lateral trimline exhibited a more consistent and significant reduction in stiffness as the projection of the trimlines onto the sagittal plane decreased. The buckling with certain reduction in trimlines projection on the sagittal plane on the medial side, leads to the drastic stiffness reduction and structural failure. The results show the importance of trimlines cut distal to the ankle. On the lateral side, moving trimlines posteriorly towards the ankle beyond 70 mm leads to a sudden drop in the stiffness of the AFO. In this AFO, 70 mm is 25 % of the foot length.

This study identified a critical threshold on the lateral side, distal to the ankle joint for the distance between the trimline and the ankle plane under a given load. Below this threshold, the AFO's stiffness in dorsiflexion was significantly compromised, which led to buckling. This shows the importance of maintaining a sufficient lateral trimline distance from the ankle plane to ensure structural stiffness and effective rigidity without structural failure.

Moreover, on the medial side distal to the ankle joint, the finite element model was not solved when the trimline distance to the ankle plane was below 20 mm, because of instability of the structure. This can show a potential buckling threshold [23] closer to the ankle joint, the model's limitations prevent confirming the threshold existence. Alternative testing methods, including experimental work, are necessary to explore the behaviour of the AFO at these extreme reductions in trimline projection.

The significant effects of trimlines, both distal and proximal to the ankle, highlight the need for a more precise prescription and manufacturing process. This includes incorporating trimline measurements into standard practice and quality control to ensure consistency and effectiveness. While defining a specific threshold for acceptable trimline cuts at the ankle joint is beyond the scope of this study, our methodology provides a foundation for establishing such guidelines in future research. To integrate trimline location measurements into routine clinical practice, a clinically relevant and accurate measurement method is essential. This method should be simple, user-friendly, and feasible for everyday use without requiring expensive or specialised equipment.

4.1. Significance

Despite existing ISO definitions for ankle-foot orthoses (AFOs), the lack of standardised terminology for different AFO subtypes leads to inconsistencies in research, clinical interpretation, and education [24]. This study highlights the importance of quantifying trimline placement when designing rigid AFOs for dorsiflexion assist, as optimising trimlines can achieve the desired stiffness while maintaining patient comfort. Clinicians and manufacturers should maximise sagittal trimline projection with patient comfort in mind. Addressing these gaps in standardisation will enhance research design, support meta-analyses, improve intervention clarity, and ultimately refine clinical practice.

4.2. Limitations and future research

This study used a validated parametric FE model, supported by experimental data. Further research is needed to validate these findings with manufactured AFOs and to explore subject-specific parameters in clinical practice through collaboration between scientists, clinicians, and orthotists. In this study, a dorsiflexion moment of 30 Nm, relevant for paediatric usage, was applied for direct comparison with current literature. Although higher loads are typically experienced by adult AFO users, and quasistatic testing did not account for loading rate or the viscoelastic properties of polypropylene, testing at higher, clinically relevant moments and loading rates would not change the conclusions regarding the sensitivity of AFO stiffness to thickness and reinforcement design. Additionally, a clinical study should investigate the balance between trimline placement and user comfort. A comprehensive analysis of these factors will help develop evidence-based guidelines for optimal AFO design, ultimately improving clinical outcomes.

5. Conclusions

The placement of trimlines significantly influences AFO stiffness, with even a one-millimeter difference capable of altering its mechanical properties. Consequently, careful determination of trimline position is essential during prescription, and measuring trimline distances as part of post-manufacturing quality control is crucial for consistency and effectiveness.

CRediT authorship contribution statement

Sara Behforootan: Formal analysis, Investigation, Writing – original draft. **Chatzistergos Panagiotis:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing. **Eddison Nicola:** Conceptualization, Writing – review & editing. **Chockalingam Nachiappan:** Conceptualization, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Nachiappan Chockalingam reports financial support was provided by Orthopaedic Research UK. Nicola Eddison is the current chair of British Association of Prosthetists and Orthotists; Nachiappan Chockalingam is the Editor in chief of the journal. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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