Title: A quantitative analysis of optimum design for rigid ankle foot orthoses: the effect of thickness and reinforcement design on stiffness.

Running header: Rigid AFO design optimisation

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None to declare.

Abstract (max 250 words):

Aim: An ankle foot orthosis (AFO) which is prescribed to be rigid should only deform a small amount to achieve its clinical goals. Material thickness and the design of reinforcing features can significantly affect AFO rigidity, but their selection remains based on anecdotal evidence. This study aims to quantify the effect of these parameters on AFO stiffness and to set the basis for quantitative guidelines for the design optimisation of rigid AFOs.

Methods: A polypropylene AFO was produced according to UK standard practice and its stiffness was experimentally measured for 30Nm of dorsiflexion. Its geometry and mechanical characteristics were utilised to create a finite element (FE) model of a typical AFO prescribed to be rigid. Following validation, the model was used to quantify the effect of material thickness and reinforcement design (i.e., reinforcement placement, length) on stiffness. A final set of AFO samples was produced to experimentally confirm key findings.

Results and conclusions: For a specific AFO geometry and loading magnitude, there is a thickness threshold below which the AFO cannot effectively resist flexion and buckles. FE modelling showed that stiffness is maximised when reinforcements are placed at the anterior-most position possible. This key finding was also experimentally confirmed. The stiffness of an AFO reinforced according to standard practice with lateral and medial ribbing was 4.4Nm/deg±0.1Nm/deg. Instructing the orthotic technician to move the ribbings anteriorly increased stiffness by 22%. Further stiffening is achieved by ensuring the reinforcements extend from the footplate to at least two-thirds of the AFO's total height.

Clinical relevance: A significant number of people rely on AFOs to carry out their activities of daily living, remain independent, reduce their pain, and reduce the risk of symptom deterioration. Currently, there are no guidelines which dictate how an AFO prescribed to be rigid should be designed to ensure it is rigid enough to do the job it is meant to do. The present study helps address this gap by offering evidence-based guidelines to optimise the design of reinforcement features such as ribbings to maximise rigid AFO stiffness. It also provides the first quantitative data on the effect of thickness on stiffness to inform guidelines for optimum thickness selection.

Key points:

- For specific AFO geometry and loading magnitude, thickness should be kept above a specific threshold to avoid excessive flexion due to AFO buckling.
- AFO stiffness is maximised when reinforcements are placed at the anterior-most position possible.
- Further stiffening is achieved by ensuring they extend from the footplate to at least two-thirds of the total distance between the AFO's base and proximal strap

1. Introduction:

An ankle foot orthosis (AFO) which is prescribed to be rigid should only deform a small amount from its original shape to achieve its clinical goals[1,2]. A lack of adequate rigidity or a compromise in an AFO's structure can result in pain (for example in an osteoarthritic ankle where movement is not desirable). It can also result in poor gait if the shank is not in the optimum position at mid-stance, which is essential for stability and lower limb progression[3,4]. More specifically, the shank should be inclined from the vertical position which brings the knee joint centre over the middle of the foot during temporal mid-stance[5].

Rigid AFOs also play an important role to facilitate the desired stretching of the musculature of the lower limbs[3,4] for the treatment of neurological disorders which increase the risk of lower limb contractures (e.g., cerebral palsy, multiple sclerosis, cerebral vascular accidents). In this case an inadequately rigid AFO increases the risk for the development of contractures which reduce mobility, cause additional pain, and put the patient at increased risk of developing pressure sores. These have a detrimental effect on quality of life and increase the need for invasive lengthening of muscles in the lower limbs[4].

Despite the importance of adequate rigidity, to date, there is still a paucity of structured scientific studies which have explored the effects of each element of AFO design on their stiffness[6,7]. The historical view is that the shape of the ankle trim lines is the most important parameter that affects AFO stiffness[8–10]. However, this view is based on a research paper from 1975, which provided no specific data or guidelines to inform the design of rigid AFOs[11].

In 1975 the researchers also stated *"Obviously, the thicker the walls the more rigid the orthosis"*[11]. Later in 1981 further reports indicated that increasing the thickness of the material in AFOs had *"little benefit"*[12]; instead advocating the use of ankle reinforcements as the answer to increasing stiffness. Reinforcement design features include the use of carbon fibre reinforcements and ribbings or corrugations around the ankle[13–15]. Although the clinical impact of such design features has been debated and discussed, the literature does not provide any data to inform optimal AFO design[12].

Four decades on, prescription designing AFOs is still based on anecdotal evidence and historical practice and without any scientific and objective guidance on how to control rigidity. This often leads to sub-optimal structures and poor patient outcomes[3] or require a re-make of the AFO which presents an additional cost to patients and health care systems. We then have the added issue of a lack of standardisation in manufacturing. Thus, when a clinician requests an AFO made to a specific thickness and with specific reinforcing elements ten different technicians will provide ten different devices, while the same technician will not produce an identical device twice.

Without essential data on the impact of each element of the AFO design on its stiffness, it is not possible to devise prescription guidelines and standardise manufacturing and reduce disparities in treatment outcomes[16]. In this context, the present study aims to quantify the effect of thickness on the stiffness of AFOs which are prescribed to be rigid and to explore the parameters that define the optimal design of reinforcements. Considering that the focus of this study is on AFOs that are designed to be rigid, optimum reinforcement design is understood as the design that maximises stiffness without a significant increase in AFO weight or cost.

2. Methods

For this study, quasistatic mechanical testing is combined with computer modelling to create and validate a finite element (FE) model of a typical rigid AFO. The developed FE model is then used in a series of virtual experiments to quantify the effect of thickness and reinforcement design on AFO stiffness.

2.1 Reference AFO sample

A rigid AFO[2] was produced by an orthotic technician with over 15 years' experience (who was blinded to the study) to the specifications most commonly used by UK orthotists[17] (figure 1a). The standardised procedure for AFO provision within the National Health Service (NHS) in the United Kingdom was used. More specifically, the AFO was produced using the standard method of drape-forming over a positive plaster cast from a 4.5 mm thick polypropylene sheet (North Sea Plastics ltd.). The positive plaster case was created for a healthy subject described as an adult man aged between 18 and 45 years, weighing between 64 and 88 kg, and between 173 and 188 cm in height[17].

On receiving the sample for testing, the actual thickness of the produced AFO was measured using a digital calliper at the areas where high stresses are expected during dorsiflexion, namely at the ankle trim lines[18–20]. Six equally spaced measurements were on the medial and six on the lateral ankle trim line (figure 1a). The average thickness was 3.27mm±0.11mm.

2.2 Mechanical testing

AFO stiffness was assessed by measuring how much the AFO flexed under a clinically relevant dorsiflexion torque (30Nm)[14]. AFO dorsiflexion was imposed using a torsion device which was adapted for this purpose (figure 1b). The testing device comprised a fixed support plate which was connected to a torque load cell (Applied Measurements Ltd, DTD-F-50Nm, sensitivity:1.0mV/V, accuracy:±0.05Nm) and a rotating arm which was controlled by a motor. The AFO was fixed on the support plate and the ankle joint axis was aligned with the rotation axis of the testing device[21]. The rotation axis of the ankle joint was approximated by the midpoint of a straight line connecting the apex of the lateral malleolus to the apex of the medial malleolus[19,22]. To load the sample, the rotating arm of the device was fitted with a 3D-printed shank. The 3D-printed shank was fixed inside the AFO using the AFOs proximal strap (figure 1b). During testing, the shank was rotated at 1deg/min around the ankle joint while the reaction moment at the support base was recorded at 100Hz. Loading was terminated when dorsiflexion torque became equal to 30Nm[14]. At that point, the total dorsiflexion angle of the AFO's shank relative to its footplate was measured using a pair of digital inclinometers (Neotec, resolution= ±0.01deg, accuracy= ±0.1deg) (figure 1b). Equivalent stiffness was calculated as the applied moment divided by the maximum flexion angle. Each test was repeated three times and their average was used as the final measurement of equivalent stiffness.

2.3 FE model design

The geometry of the reference AFO was digitised using a 3D scanner (HandySCAN BLACK™ Elite, Creaform) and imported into ANSYS (ANSYS-2021.R1, Canonsburg, PA, USA) following minor corrections using Solidworks (figure 2a). The final FE model was meshed using 9,349 shell elements (Shell-281). Mesh convergence analysis was conducted to eliminate mesh dependency phenomena. The AFO was assumed to have a uniform thickness[19] equal to the reference AFO's thickness. To simulate mechanical testing, the model's footplate was fixed and a dorsiflexion moment of 30Nm was imposed at the areas where the proximal strap was connected to the AFO. The mechanical behaviour of polypropylene was experimentally assessed and simulated as linearly elastic perfectly plastic (Young's modulus = 866 MPa, yield stress = 21.5 MPa). Please see Supplementary Material for more information on material characterisation. The Poisson's ratio was assigned as 0.43 based on literature[23].

2.4 FE model validation

The accuracy of the FE model was directly validated against mechanical testing. More specifically, the experimentally measured dorsiflexion angle of the reference AFO for a rotational moment of 30Nm was 4.7deg±0.1deg. The FE predicted flexion for the same loading was 4.8deg (figure 2b). The observed difference of 0.1deg is within the margins of error of testing.

2.5 FE parametric analysis

Following validation, the developed FE model was used to perform three series of virtual experiments. The first focused on the effect of material thickness on the AFO's stiffness, and the second and third on the effect of positioning and length of reinforcing elements, respectively.

2.5.1 Effect of material thickness

Starting with the thickness of the reference AFO as baseline, the thickness of the FE model was increased or decreased (5% increments) to a maximum of 25% thicker or 25% thinner, respectively (table 1). The sensitivity of AFO's stiffness to thickness was assessed.

2.5.2 Effect of reinforcement placement

To decouple the effect of placement from the specific design characteristics of individual reinforcing elements, an idealised reinforcement was considered. More specifically the reference AFO was reinforced by adding a beam with a circular cross-section (radius=5mm) made from the same material as the rest of the AFO. The reinforcing beam mirrored the contour of the AFO's trim lines and was initially placed in such a way that it passed through the ankle rotation axis. With regards to its length, the reinforcement extended from the footplate (80mm distal to the ankle axis) to the AFO's proximal strap (316mm proximal to the ankle axis).

To assess the effect of placement, the reinforcing beam was moved to the anterior-most possible position (i.e., fully aligned with the AFO's trim line), to the posterior-most position and to positions in-between (increments of 5mm)(table 2). This process was done separately for the medial and lateral sides.

2.5.3 Effect of reinforcement length

The length of the reinforcing beam was gradually reduced by moving its proximal end closer to the ankle axis (40mm increments) (table 3). Zero proximal length meant that the reinforcing beam started at the footplate and ended at the level of the ankle axis. The same process was also followed for its length in the distal direction. In this case, length was gradually reduced (20mm increments) (table 3) and zero distal length meant that the reinforcing beam extended from the ankle axis to the proximal strap. For these simulations, AFO thickness was equal to baseline and the reinforcing beam was placed in its optimal antero-posterior position. The optimal antero-posterior placement was decided based on the results of the previous parametric analysis as the one that achieved maximum equivalent stiffness.

2.6 Experimental validation of key findings

Key findings regarding the optimal position and length of reinforcements were experimentally validated after the end of all FE simulations. To this end, the technician who manufactured the reference AFO was asked to produce another AFO for the same leg cast, but this time to reinforce it with a medial and a lateral ridge. Initially, no specific instructions were provided regarding the position or length of the ridges for this reinforced AFO (RAFO-1). Once this sample was ready, the technician was asked to produce a second reinforced AFO (RAFO-2), but this time they were instructed to place the reinforcement to the position indicated by the FE analysis to be the optimum. The length of the ridges was the same as in RAFO-1. For the last sample (RAFO-3) the technician was asked to keep the ridges at their optimal position (same as RAFO-2) and to adjust their length to the optimum according to the FE analysis. If the results of the FE parametric analysis regarding optimum reinforcement are reliable and clinically relevant, then RAFO-2 should be significantly more rigid than RAFO-1. RAFO-3 should be the most rigid of the three.

3. Results

3.1 Finite element parametric analysis

3.1.1 The effect of thickness

Starting from the scenario for the thickest material (thickness=4.09mm) equivalent stiffness decreased linearly with thickness down to a thickness of 3.60mm (figure 3). Further thinning after this point led to a significantly higher reduction in stiffness. Indicatively, a reduction in thickness from 4.09mm to 3.60mm (12% relative thickness reduction) reduced equivalent stiffness from 14.1Nm/deg to 10.5Nm/deg (26% stiffness reduction). The same increment of thickness reduction to 3.11mm (14% further relative thickness reduction) reduced equivalent stiffness to 4.3Nm/deg (59% further stiffness reduction). This sudden decrease in equivalent stiffness is triggered by buckling of the AFO leading to visible bulging at the ankle area (figure 3). Further reduction of thickness led to flexion angles that were too large for the intended use (table 1).

3.1.2 The effect of reinforcement placement

Placing the reinforcement in a position anterior to the ankle axis substantially increased the AFO's stiffness (figure 4). Anterior-most placement appears to be optimal. More specifically, adding a medial or a lateral reinforcement at the ankle axis increased equivalent stiffness by 35% and 45%, respectively, relative to the unreinforced reference AFO. Moving the reinforcements to their anterior-most position further increased equivalent stiffness to 63% and 31% respectively (table 2). Moving the reinforcing beams in positions posterior to the ankle axis significantly compromised their capacity to stiffen the AFO (figure 4).

3.1.3 The effect of reinforcement length

Reducing the length of the reinforcements by moving their top end closer to the ankle joint had a very small effect on equivalent stiffness when the distance between the top end and ankle joint was ≥160mm. Lowering the top-end beyond that point substantially reduced the AFO's stiffness (figure 5a). Indicatively, an AFO with a medial reinforcement that started at the footplate and ended at 160mm from the ankle joint was less than 0.5% more flexible than the AFO with a reinforcement that reached the proximal strap (table 3). Results for lateral reinforcements followed the same trend (figure 5).

Reducing the reinforcements' length by moving their bottom end closer to the ankle joint had a significant detrimental effect on stiffness. In these cases, maximum equivalent stiffness was achieved by reinforcements that extended all the way to the AFO's footplate (figure 5b). Raising the bottom end of the medial or lateral reinforcement all the way up to the ankle joint reduced their equivalent stiffness by 27% and 28% respectively (table 3).

3.2 Experimental validation of key findings

When no specific instructions were given to the technician regarding the reinforcements, the ribbings in RAFO-1 were placed ≈1cm posterior to the ankle axis (figure 1c). Their bottom-end was ≈5cm distal to the ankle axis (≈3cm from the AFO's footplate) and their top-end ≈5cm proximal to the ankle axis. The equivalent stiffness of RAFO-1 was 4.4Nm/deg±0.1Nm/deg and it was the lowest of the three reinforced AFOs.

For RAFO-2 the technician was asked to move the ribbing as much as they could in the anterior direction while keeping the bottom and top ends (and thus the reinforcement's length) the same as RAFO-1. This led to an AFO with ribbings placed ≈1cm anterior to the ankle axis (figure 1d). This modest change in placement significantly increased equivalent stiffness to 5.4Nm/deg±0.1Nm/deg (22% stiffening relative to RAFO-1).

For RAFO-3, the technician was asked to keep the placement of the ribbing the same as in RAFO-2 but to extend it so that its top end was 160mm proximal to the ankle axis (figure 1e). RAFO-3 achieved the highest stiffness of the three reinforced samples: 8.3Nm/deg±0.1Nm/deg (83% stiffening relative to RAFO-1).

With regards to thickness, RAFO-1 and RAFO-2 had very similar thicknesses; 3.00mm±0.04mm and 3.03mm±0.05mm respectively. However, RAFO-3 appeared to be significantly thicker (3.46mm±0.10mm).

4. Discussion

This study quantified the sensitivity of the stiffness of AFOs which are prescribed to be rigid to their thickness and to the design of reinforcements. Even though the samples and FE models that were used corresponded to an adult AFO the conclusions drawn from these sensitivity analyses are applicable to any AFO that is prescribed to be rigid, this also includes paediatric AFOs.

The results presented here showed that to maximise an AFO’s stiffness, reinforcements should: a) be placed as anteriorly as possible, b) their bottom-end should reach as close to the footplate as possible and c) their top-end should extend adequately close to the proximal strap (e.g., two-thirds of the total distance between base and proximal strap).

These guidelines for optimal reinforcement were formulated based on a validated computer model for an idealised reinforcing element. Their validity and clinical relevance were directly tested and verified for AFOs reinforced using ribbings. More specifically, instructing an orthotist to place the ribbings as anteriorly as possible led to the production of an AFO (RAFO-2) that was 22% stiffer compared to standard practice (RAFO-1). It is important to highlight that there was no trade-off for this significant improvement in performance. The weight and cost of the device remained the same. When additional instructions about the optimal length of the reinforcement were also provided, the produced AFO’s (RAFO-3) stiffness increased by an additional 54% (relative to RAFO-2).

RAFO-3 was also significantly thicker than the rest of the AFOs tested within this study. Whilst this showcases the arbitrary nature of AFO manufacturing process and a strong need for standardisation, it makes it difficult to directly quantify the effect of optimal reinforcement length on AFO stiffness. One could argue that the observed improvement is the combined effect of optimal length and increased thickness. On the contrary, the thickness of RAFO-2 was very similar to RAFO-1 which clearly indicates that the observed improvement is caused by the simple act of moving the ribbing to a more anterior position.

The dorsiflexion angles of the samples ranged between 2.6deg and 6.8deg which is very similar to results from the literature about paediatric rigid AFOs for the same magnitude of applied dorsiflexion moment[14].

The observed % stiffening that was achieved in RAFO-2 and RAFO-3 are in line with the predictions of our validated FE model. This enhances confidence on the robustness of methods and the validity of the produced guidelines for optimal reinforcement. The magnitude of the % improvement that was achieved when these guidelines were used by a single technician offers a first glimpse of the potential benefit that can be achieved. However, due to the lack of standardisation in AFO design and manufacturing these results cannot be extrapolated to estimate the improvement that will be achieved if the above guidelines for optimal reinforcement were adopted in clinical practice.

This study showed that, for a given external load, there is a threshold of thickness below which the AFO cannot effectively resist flexion and it buckles (figure 3). For the reference AFO and for the loading conditions studied here the threshold for buckling was 3.6mm. Interestingly, all samples tested as part of this study had thicknesses below this threshold. This means that, without adequate reinforcement, they would all buckle under the modest dorsiflexion moment applied here, making them too flexible for AFOs that were prescribed to be rigid.

These samples were made by the same technician from 4.5mm thick polypropylene sheets. Because of the manual nature of the manufacturing process, variability in thickness was expected. Indeed, the thickness of the produced AFOs ranged between a minimum of 3.00mm (RAFO-1) and a maximum of 3.47mm (RAFO-3). Assuming that all design, manufacturing and testing parameters were kept the same, this study indicates that material sheets with thickness ≥5.1mm would be needed to produce AFOs that don't buckle.

With regards to the limitations of this study, it is important to highlight that the thickness threshold for buckling will change with the magnitude of the dorsiflexion moment and loading speed. In this study, a dorsiflexion moment of 30Nm was used for direct comparison against current relevant literature[14]. However, loading in adult AFO users can be as high as 100Nm[24]. Moreover, the use of quasistatic testing means that the effect of loading rate and of polypropylene viscoelasticity was not assessed. Even though testing in higher, clinically relevant moments and loading rates would not change the conclusions drawn here about the sensitivity of AFO stiffness to thickness and to the design of reinforcements, the absolute values of results would indeed change. As a result, the calculation of the absolute values of the thickness threshold for buckling presented here cannot be used to inform thickness selection on a patient-specific basis. Beyond thickness and the design of reinforcements, future research towards the development of comprehensive guidelines for the prescription and design of rigid AFOs should also include the effect of trim line design, different materials and manufacturing methods as well as the specific characteristics of individual patients.

5. Conclusions

This study offers the first quantitative guidelines for optimal prescription and design of reinforcements in rigid AFOs (adult and paediatric). Maximum stiffness can be achieved by placing reinforcements at the anterior-most position that is possible and ensuring that they extend from as close to the footplate to adequately close to the proximal strap. This study also provides a blueprint for a method for optimum thickness selection, based on the thickness that avoids the buckling of the AFO under clinically relevant loading.

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Tables

Table 1: The effect of thickness on AFO flexion angle and stiffness. Changes in thickness are presented relative to the thickness of the reference AFO sample. Computational results are not available for the two thinnest scenarios (-20%, -25%) because excessive flexibility and element distortion led to non-convergence of the FE analysis.

Scenarios: Change in thickness	Thickness (mm)	**Results:** Flexion (deg)	Stiffness (Nm/deg)
25%	4.09	2.1	14.2
20%	3.92	2.3	13.0
15%	3.76	2.5	11.8
10%	3.60	2.9	10.5
5%	3.43	3.4	8.7
0% *(Reference AFO)*	3.27	4.8	6.3
-5%	3.11	7.0	4.3
-10%	2.94	9.9	3.0
-15%	2.78	16.1	1.9
-20%	2.62	*Solution did not converge*	
-25%	2.45		

Table 2: The simulated scenarios and FE results for different placements of the reinforcement in the antero-posterior (AP) direction. Positive (+) or negative (-) distances correspond to reinforcement placements in the anterior or posterior direction, respectively, relative to the ankle axis. Results with regards to the overall flexion angle for 30Nm dorsiflexion moment, stiffness and % stiffening relative to reinforcement placed at the ankle axis (AP distance from ankle=0) are presented separately for an idealised reinforcement paced at the medial and lateral side of the AFO. Negative stiffening corresponds to reduced stiffness. The distance between ankle axis and the ankle trimline was shorter in the lateral direction. As a result, fewer scenarios are available for anterior placement of a lateral reinforcement.

Scenarios:	**Results:**					
	Medial reinforcement			**Lateral reinforcement**		
AP distance from ankle (mm)	**Flexion (deg)**	**Stiffness (Nm/deg)**	**Stiffening (%)**	**Flexion (deg)**	**Stiffness (Nm/deg)**	**Stiffening (%)**
30	2.2	13.7	63	-	-	-
25	2.6	11.4	36	-	-	-
20	2.8	10.6	25	-	-	-
15	3.0	10.0	19	-	-	-
10	3.2	9.5	13	2.5	11.8	31
5	3.4	8.9	6	3.1	9.8	8
0	*3.6*	*8.4*	*0*	*3.3*	*9.0*	*0*
-5	3.8	8.0	-5	3.5	8.5	-6
-10	4.0	7.6	-10	3.8	8.0	-12
-15	4.1	7.3	-14	4.0	7.5	-17
-20	4.3	7.1	-16	4.2	7.2	-21
-25	4.3	7.0	-17	4.3	6.9	-24
-30	4.2	7.1	-15	4.4	6.8	-25

Table 3: The simulated scenarios and FE results for reinforcements extending to different distances from the ankle axis in the proximo-distal (PD) direction. The total length of the reinforcement is adapted either by moving its top-end or its bottom-end closer to the ankle axis. Positive (+) or negative (-) distances correspond to positions proximal or distal, respectively, relative to the ankle axis. Changes in stiffness are presented relative to the scenarios for longest reinforcements. Results are presented first for different positions of the top-end followed by results for different positions of the bottom end. When the position of one end of the reinforcement is changed, the other end is always kept to its most distant to the ankle position.

Scenarios:		**Results:** Medial reinforcement			Lateral reinforcement		
	AP distance from ankle (mm)	**Flexion (deg)**	**Stiffness (Nm/deg)**	**Change in stiffness (%)**	**Flexion (deg)**	**Stiffness (Nm/deg)**	**Change in stiffness (%)**
Top-end of reinforcement	*316*	*2.2*	*13.7*	*0*	*2.5*	*11.8*	*0*
	280	2.2	13.8	0	2.6	11.7	-1
	240	2.2	13.7	0	2.6	11.7	-1
	200	2.2	13.7	0	2.6	11.6	-2
	160	2.2	13.7	0	2.6	11.6	-2
	120	2.2	13.5	-2	2.7	11.3	-4
	80	2.3	12.8	-7	2.7	11.0	-7
	40	2.8	10.6	-23	3.3	9.2	-22
	0	4.4	6.8	-50	4.7	6.4	-46
Bottom-end of reinfrcement	0	3.0	10.0	-27	3.5	8.5	-28
	-20	2.7	11.2	-19	2.8	10.7	-10
	-40	2.4	12.7	-7	2.7	11.1	-6
	-60	2.3	13.0	-5	2.6	11.5	-3
	-80	*2.2*	*13.7*	*0*	*2.5*	*11.8*	*0*

Figures:

Figure 1

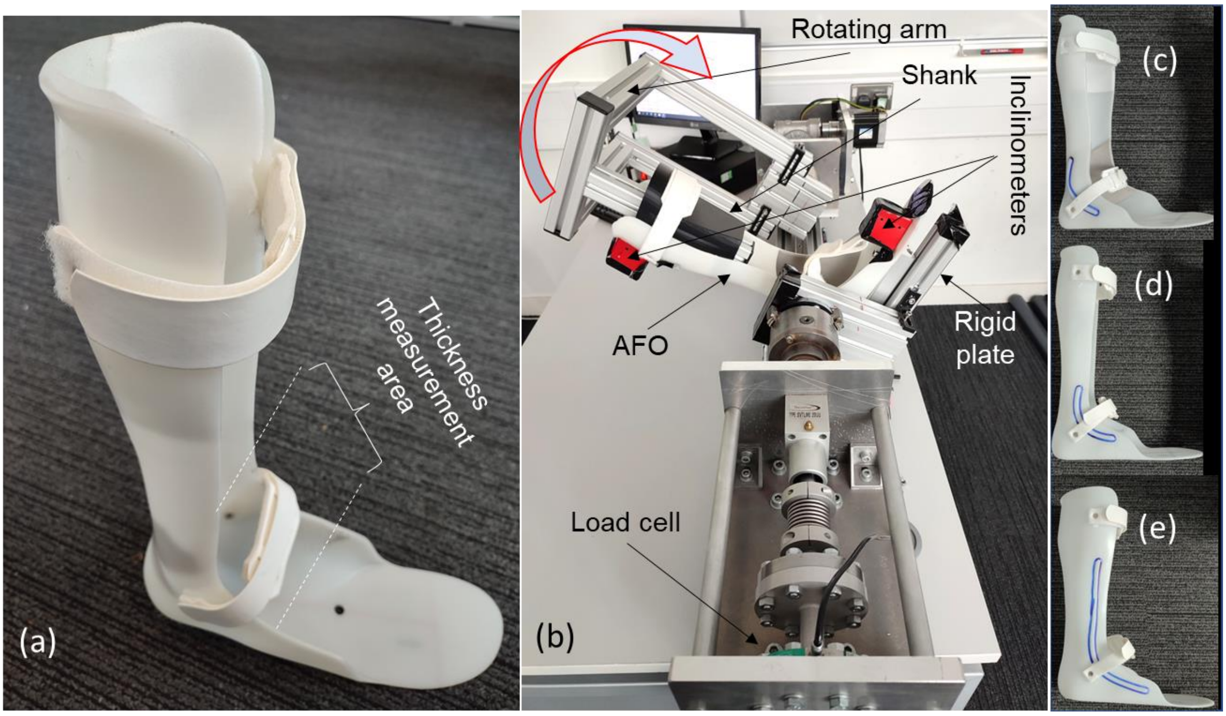

Figure 1: The reference AFO sample (a) and the testing set-up for the measurement of flexural stiffness (b). Samples reinforced with a medial and a lateral ribbing that were produced are also shown (c-e). Sample RAFP-1 (c) was produced according to standard practice, while the production of samples RAFO-2 (d) and RAFO-3 (e) was informed by the findings of this study on optimal reinforcement placement and length, respectively.

Figure 2

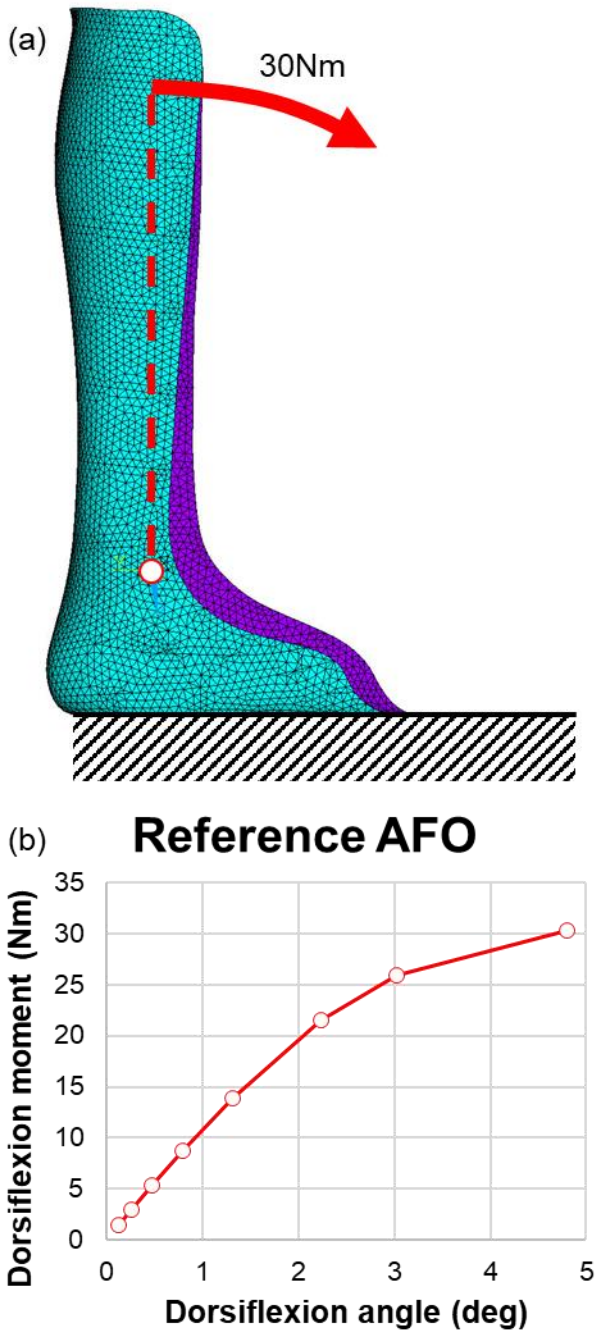

Figure 2: The FE model (a) and the stress-strain behaviour of the polypropylene that was used in this analysis (b).

Figure 3

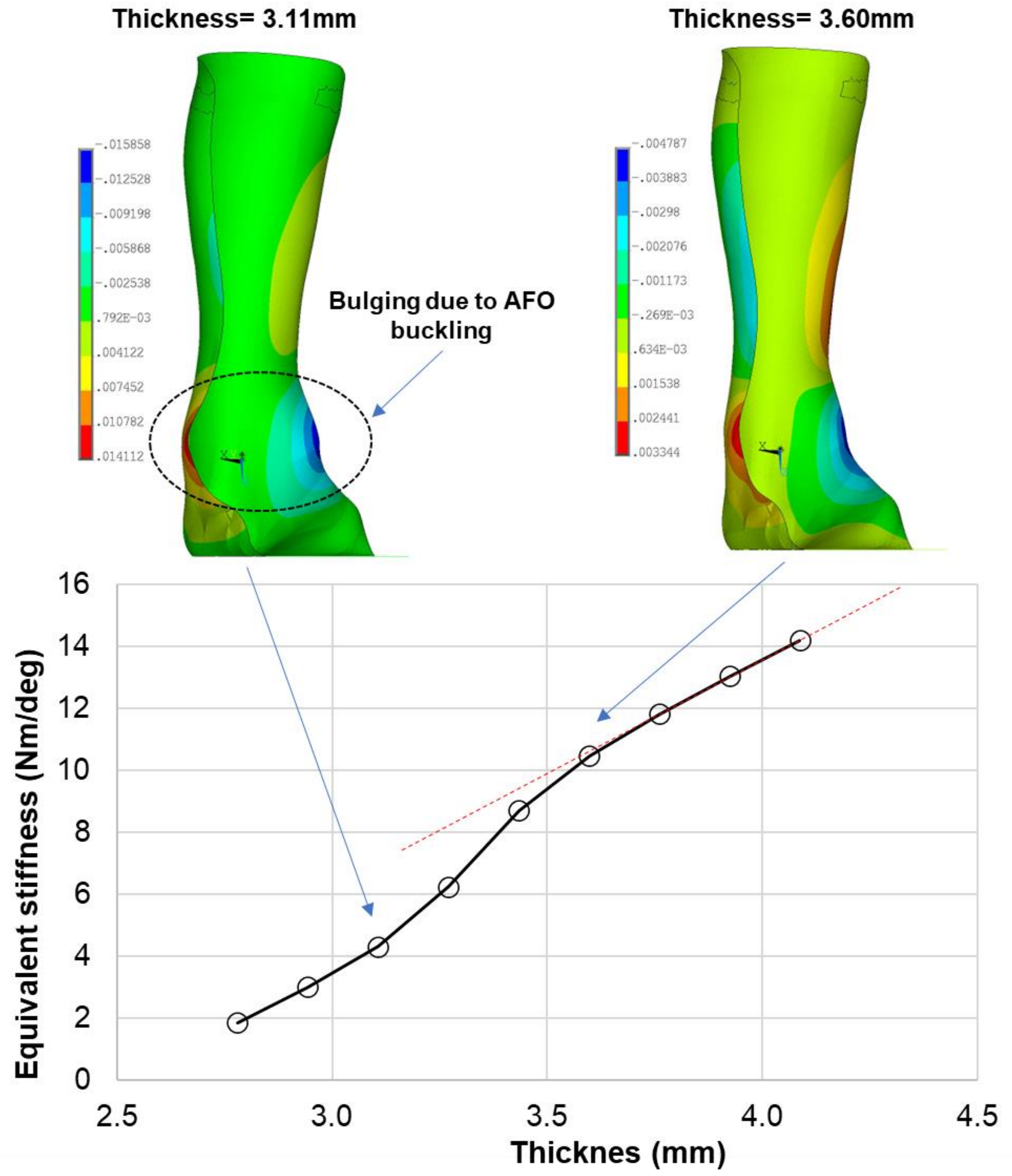

Figure 3: The effect of thickness on AFO equivalent stiffness. The deformed shapes and distributions of mediolateral displacements (in meters) for two selected AFO scenarios are also shown; one scenario where there is buckling (thickness=3.11mm) and one where there is no buckling (thickness=3.60mm).

Figure 4

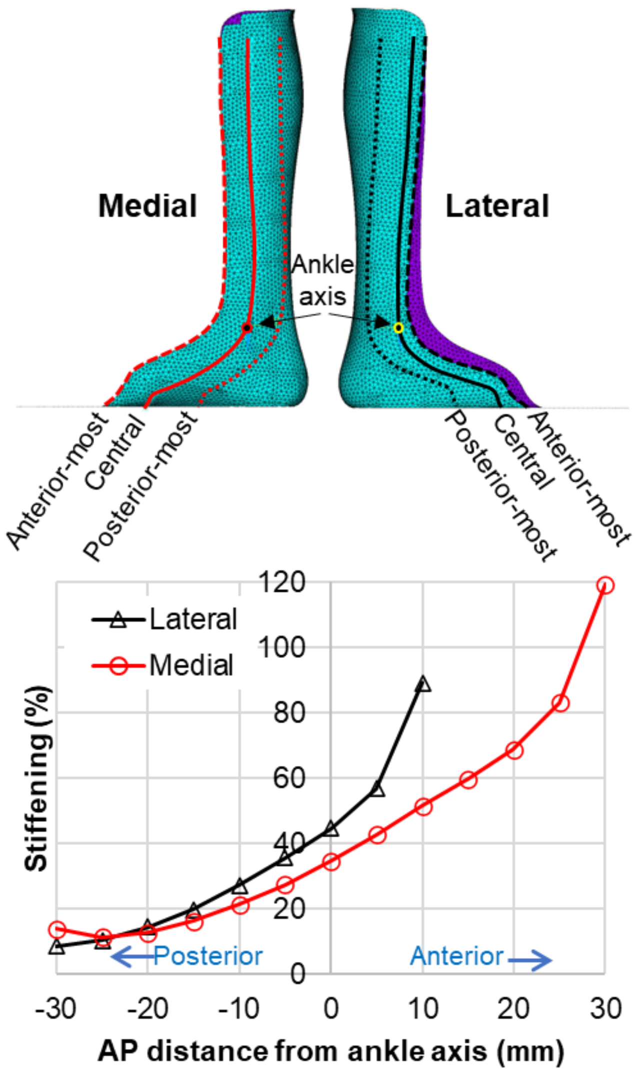

Figure 4: The effect of antero-posterior (AP) placement on the reinforcement's capacity to increase the AFO's stiffness relative to the baseline un-reinforced scenario (%stiffening). Positive (+) or negative (-) distances correspond to reinforcement placements in the anterior or posterior direction, respectively, relative to the ankle axis. The central positions (distance=0) and the anterior-most, posterior-most placements are also shown on the AFO FE model for reference.

Figure 5

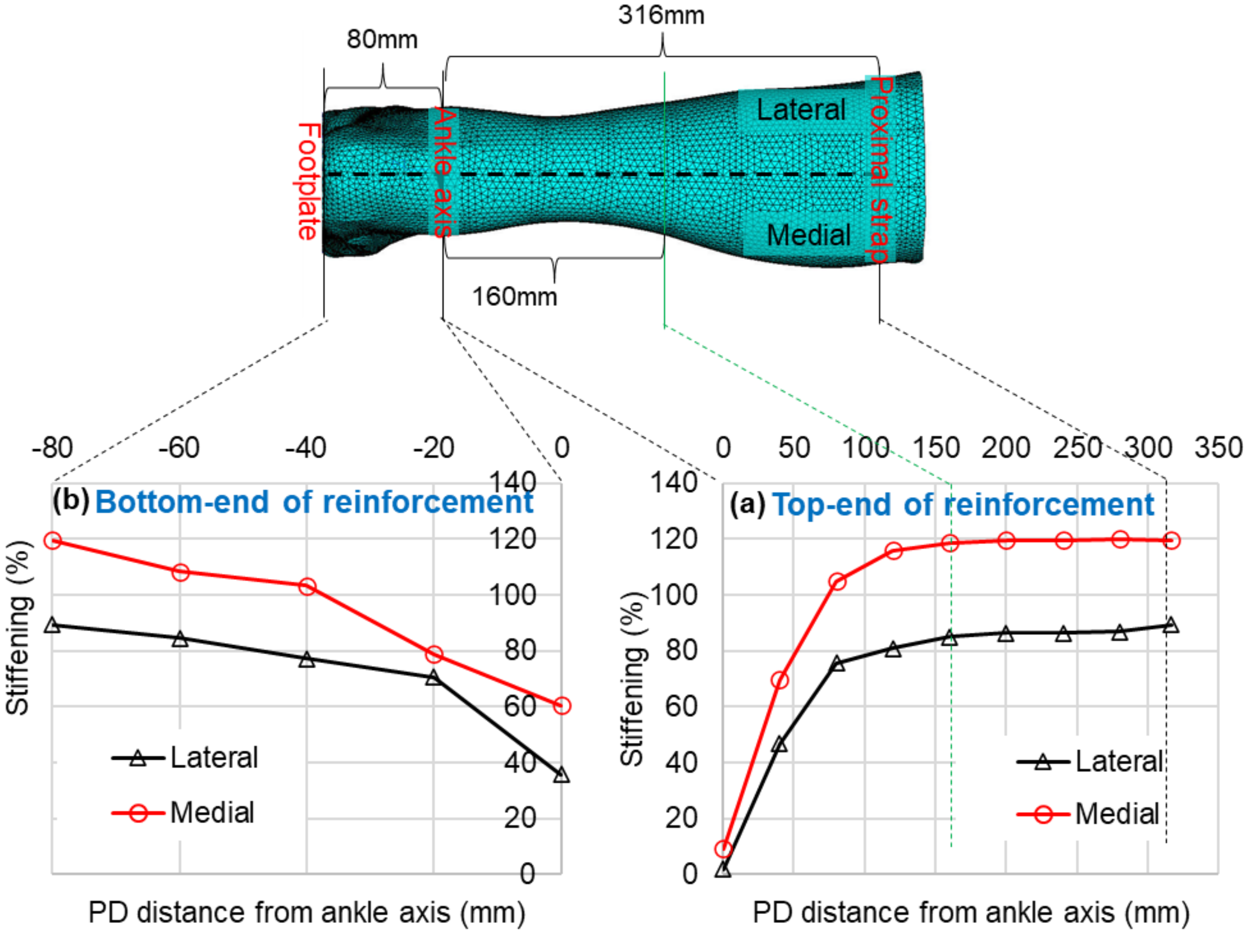

Figure 5: The effect of reinforcement length on its capacity to increase the AFO's stiffness relative to the baseline un-reinforced scenario (%stiffening). (a) Reinforcement length is changed by moving its top-end while its bottom-end is kept at the AFO's footplate. (b) Length is changed by moving its bottom-end while the top-end is kept at the height of the proximal AFO straps. Positive (+) or negative (-) distances correspond to positions proximal or distal, respectively, relative to the ankle axis. Key distances are also marked on a posterior view of the AFO FE model for reference.