

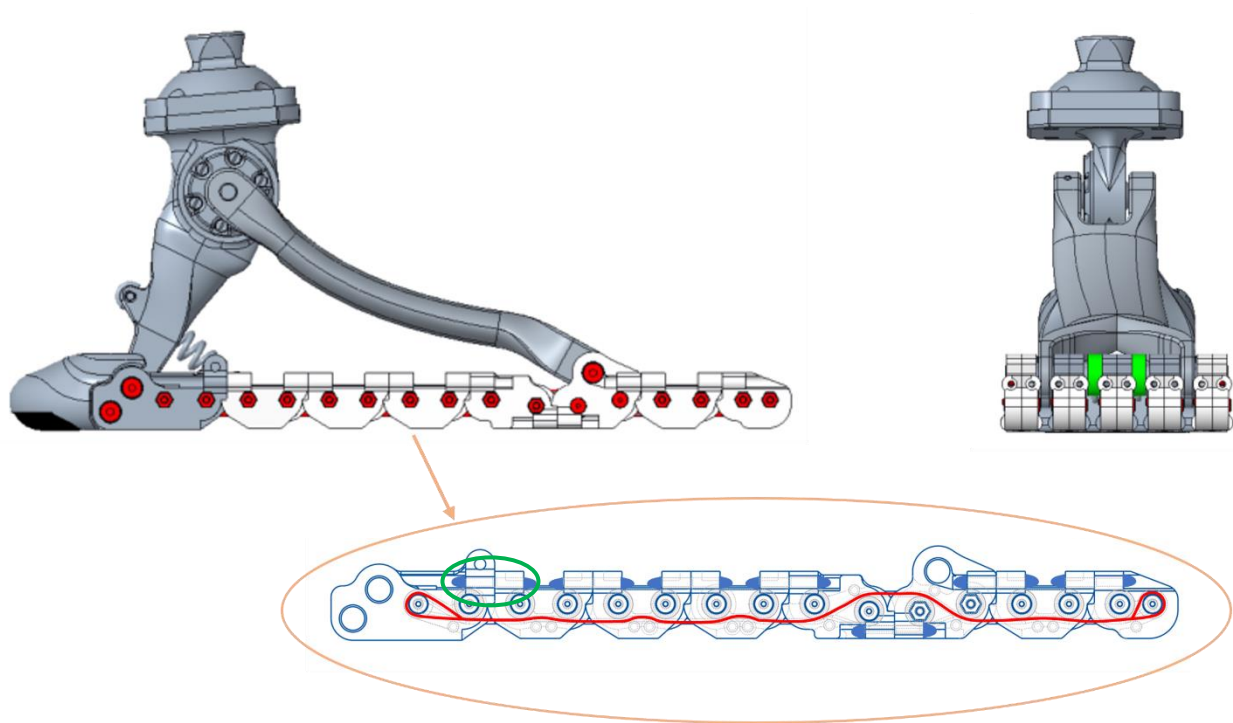
The SoftFoot Pro:
an Anthropomorphic and Adaptive Soft Articulated Prosthetic Foot
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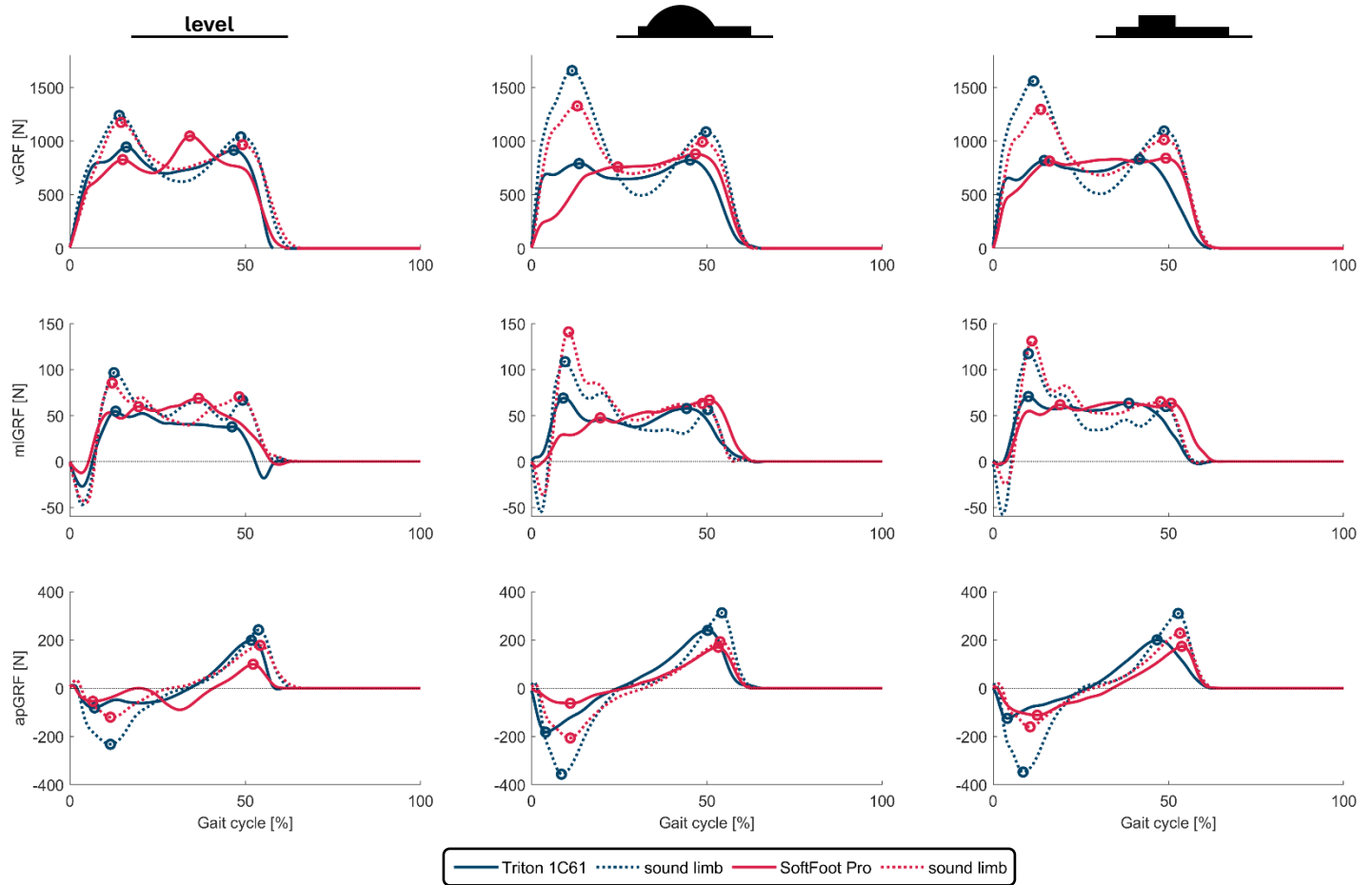
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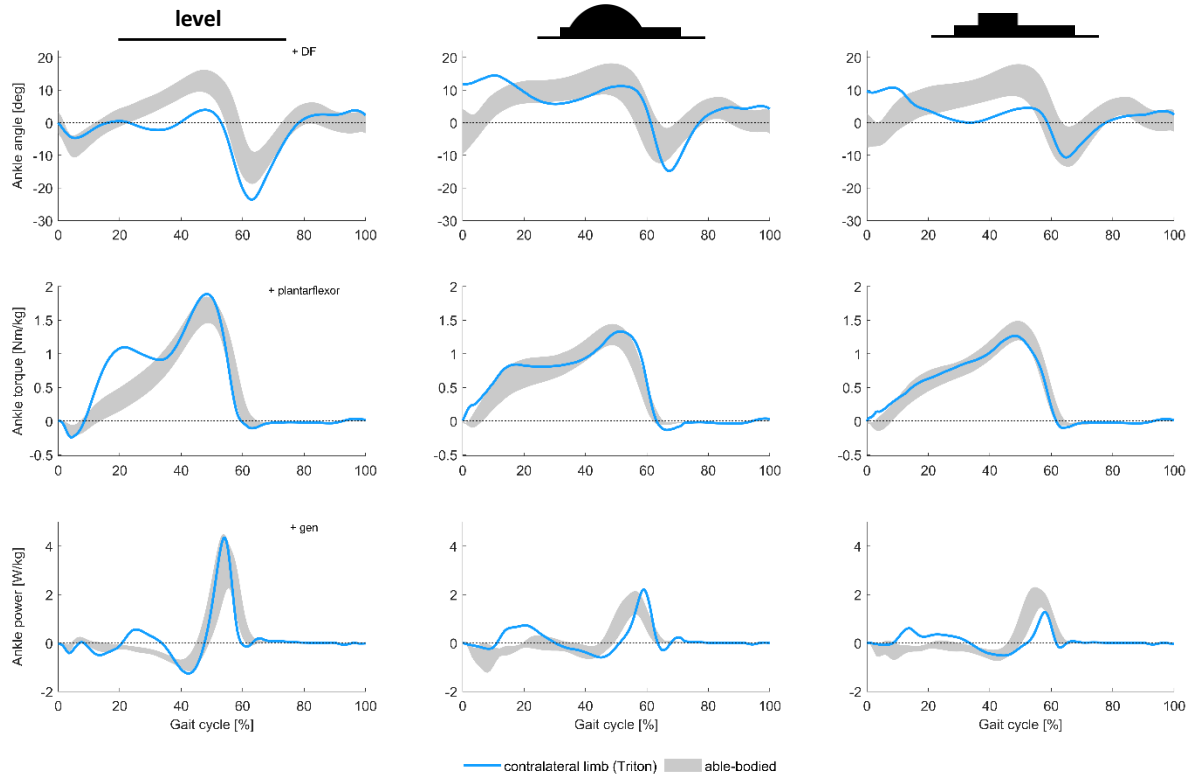
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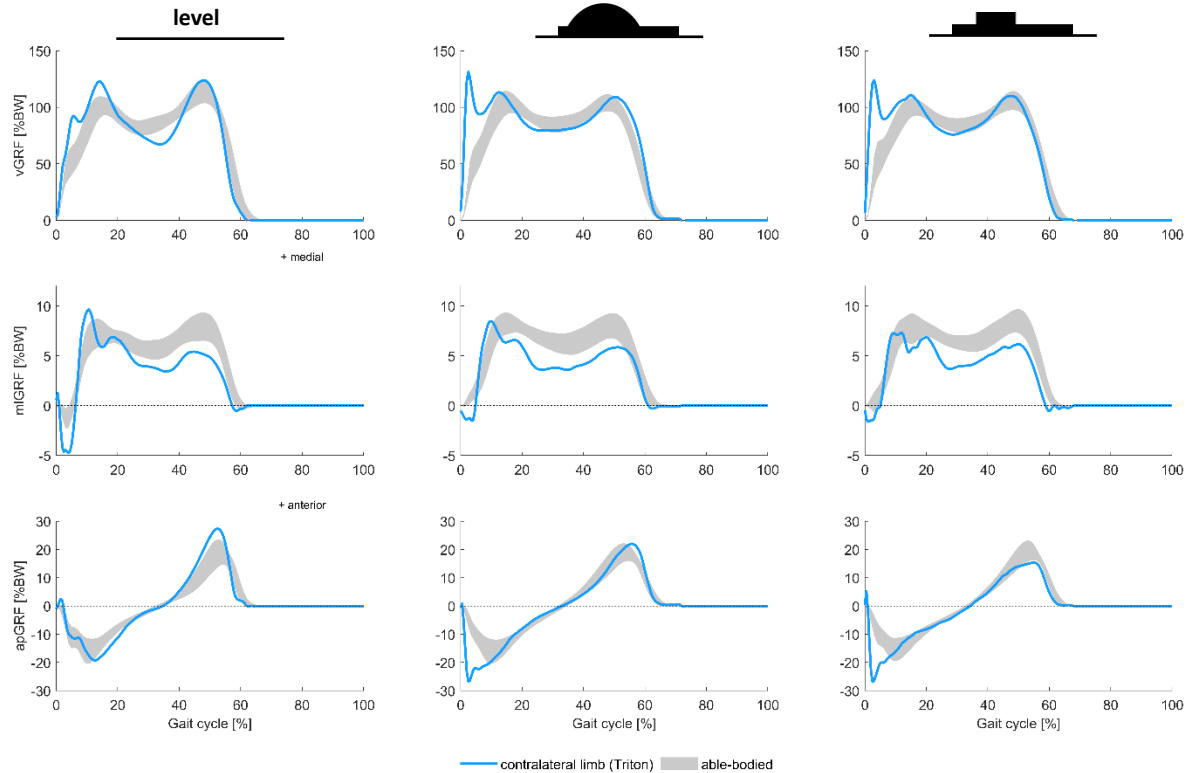
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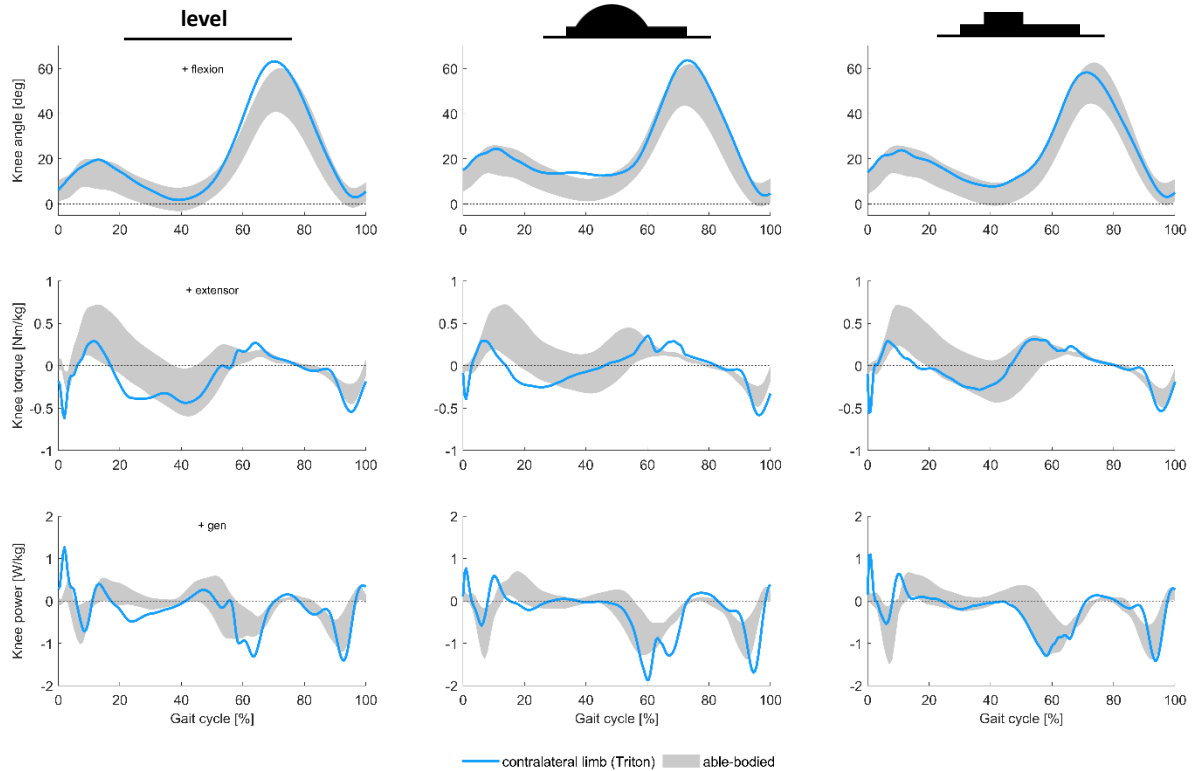
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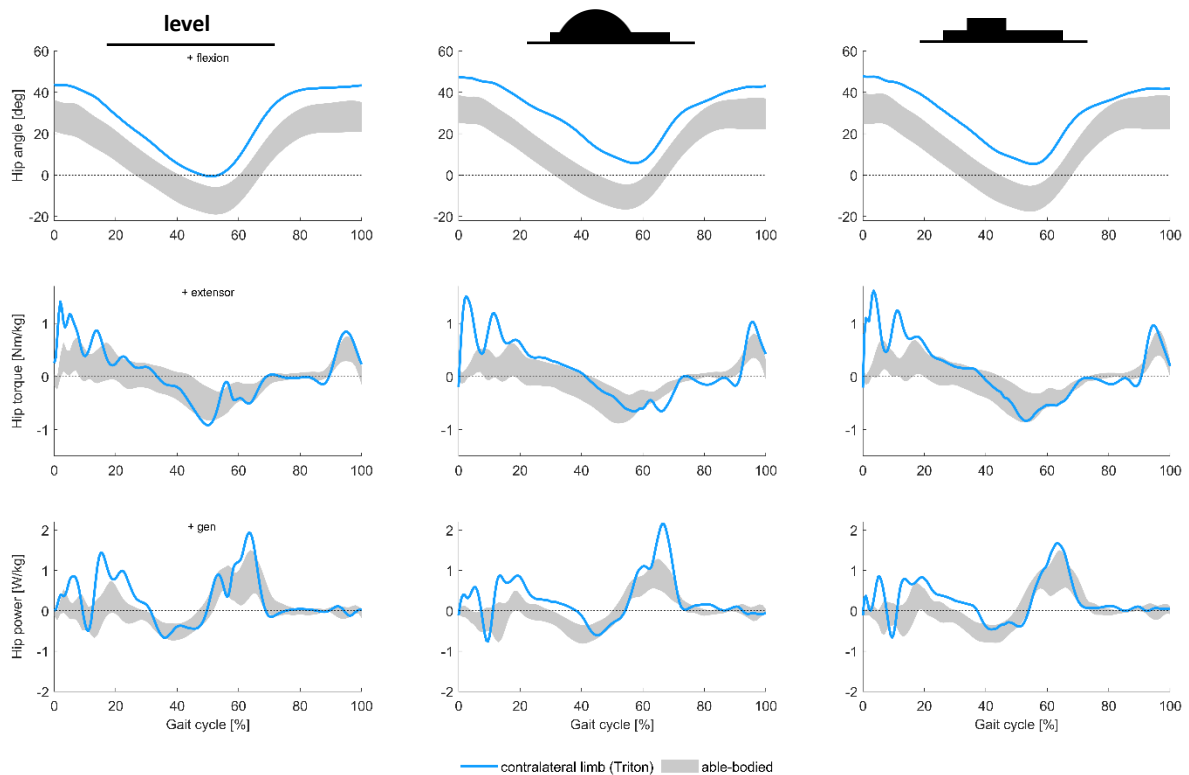
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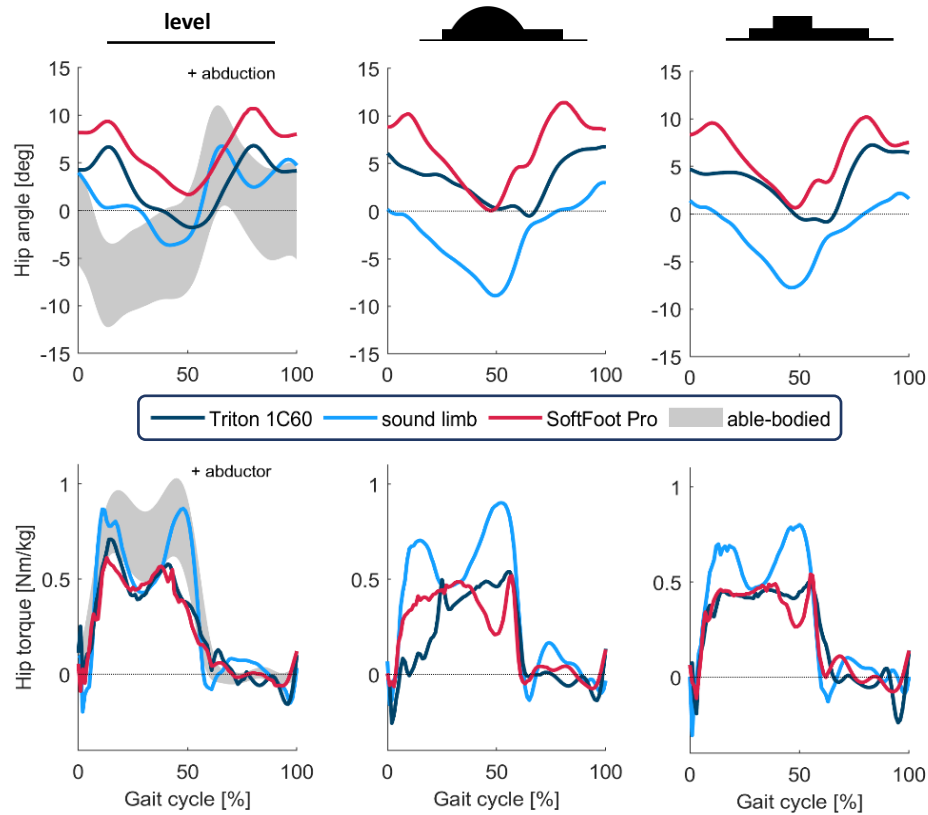
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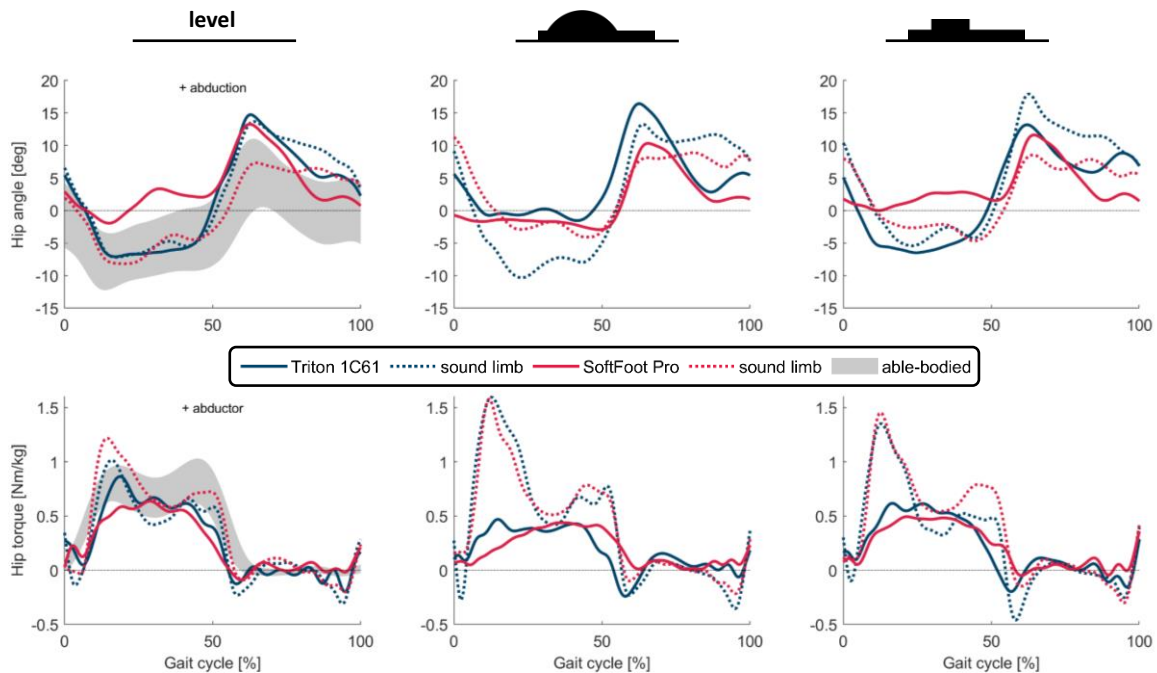
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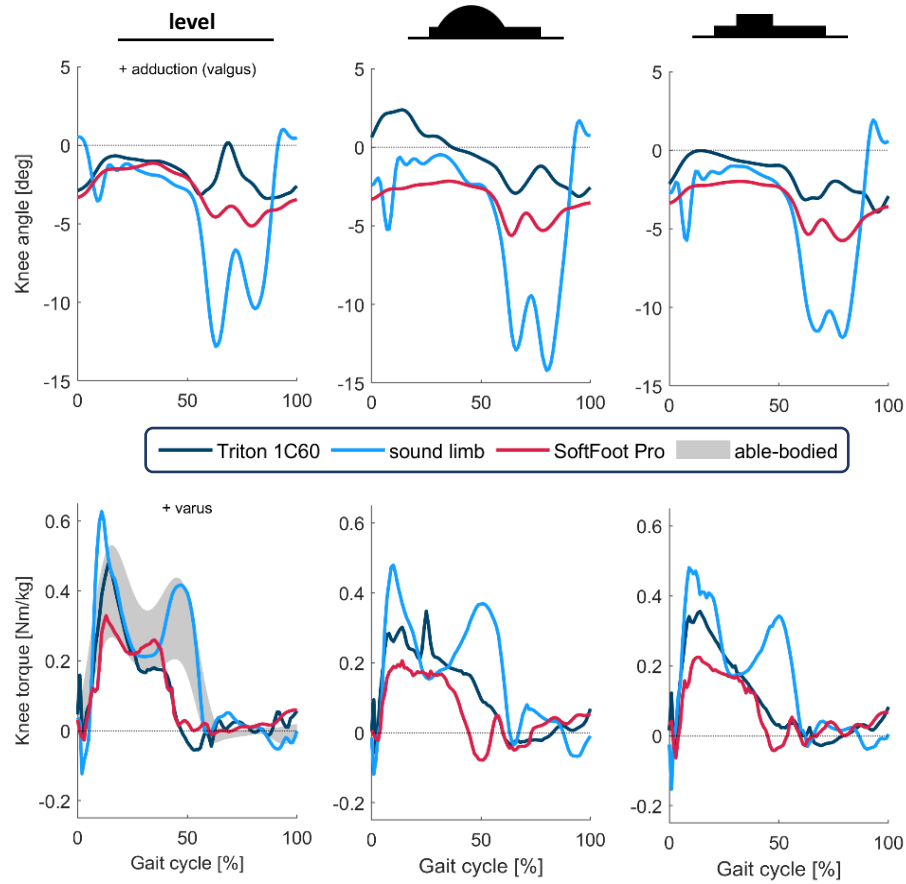
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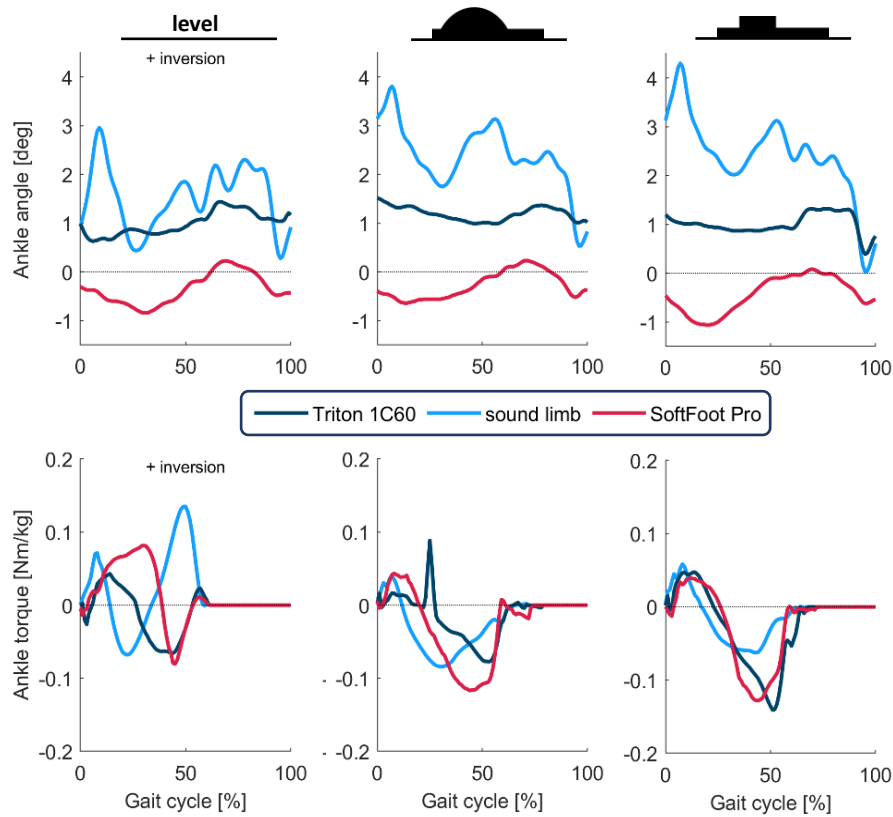
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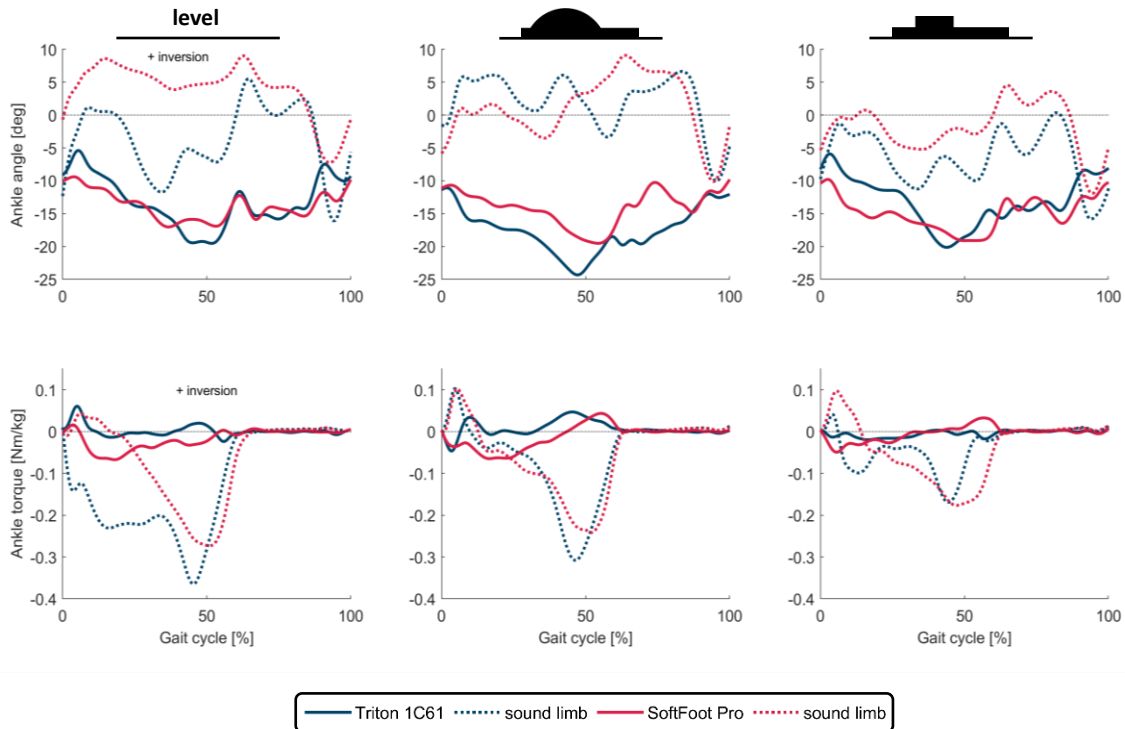
Supplementary Fig. 8 | Case study II: frontal hip angle (top) and torque (bottom) during level walking and obstacles negotiation (arch and rectangle). Mean values across 5 strides ($n=5$; 3 for level walking with the participant's prosthetic foot) for the prosthetic limb (blue solid line for the carbon fibre foot Triton, red solid line for the SoftFoot Pro), and the contralateral limb (blue dotted line when using the Triton, red dotted line for the SoftFoot Pro). Contralateral data show the stride on flat ground following the prosthetic limb's step on the obstacle. Grey-shaded areas correspond to reference data from unimpaired individuals ($\pm 1SD$)¹. Data are normalized to stride duration, with torque normalized by the participant's body mass.



Supplementary Fig. 9 | Case study I: frontal knee angle and torque (from top to bottom) during level walking and obstacles negotiation (arch and rectangle). Mean values across 6 strides ($n=6$) for the prosthetic limb (blue solid line for the carbon fibre foot Triton, red solid line for the SoftFoot Pro), and the contralateral limb when using the Triton (light blue solid line). Contralateral data represent level walking and the step on the obstacle. Grey-shaded areas correspond to reference data from unimpaired individuals ($\pm 1SD$)¹; reference data for the knee angle are lacking in Bovi *et al.*¹. Data are normalized to stride duration, with torque normalized by the participant's body mass.



Supplementary Fig. 10 | Case study I: frontal ankle angle and torque (from top to bottom) during level walking and obstacles negotiation (arch and rectangle). Mean values across 6 strides ($n=6$) for the prosthetic limb (blue solid line for the carbon fibre foot Triton, red solid line for the SoftFoot Pro), and the contralateral limb when using the Triton (light blue solid line). Contralateral data represent level walking and the step on the obstacle. Reference data for the ankle joint in the frontal plane are lacking in Bovi *et al.*¹. Data are normalized to stride duration, with torque normalized by the participant's body mass.



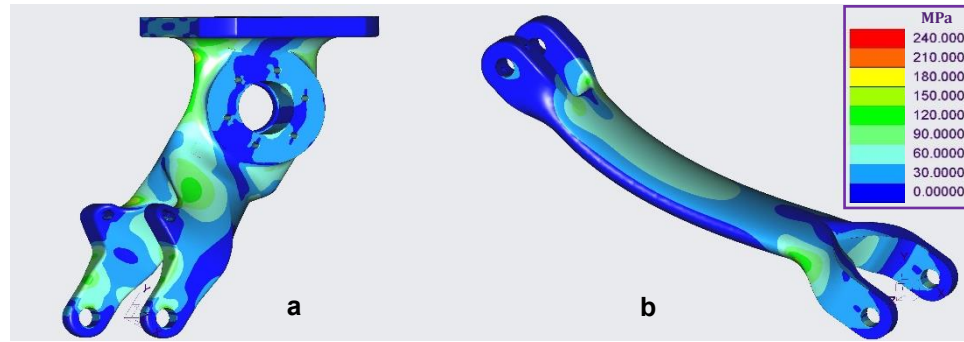
Supplementary Fig. 11 | Case study II: frontal ankle angle (top) and torque (bottom) during level walking and obstacles negotiation (arch and rectangle). Mean values across 5 strides ($n=5$; 3 for level walking with the participant's prosthetic foot) for the prosthetic limb (blue solid line for the carbon fibre foot Triton, red solid line for the SoftFoot Pro), and the contralateral limb (blue dotted line when using the Triton, red dotted line for the SoftFoot Pro). Contralateral data show the stride on flat ground following the prosthetic limb's step on the obstacle. Reference data for the ankle joint are lacking in Bovi *et al.*¹. Data are normalized to stride duration, with torque normalized by the participant's body mass.



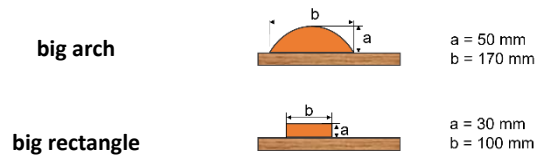
Supplementary Fig. 12 | Customised walking boots for preliminary testing of prosthetic feet with unimpaired subjects. Boots were customised by incorporating prosthetic adapters screwed to the bottom of their soles to enable attachment of the prosthetic feet. For plantar pressure mapping, sensorized insoles were placed into the shoes, under the prostheses.



Supplementary Fig. 13 | Change in shape of the human feet (first five rows) and the SoftFoot Pro (bottom row) on an arch-shaped obstacle.



Supplementary Fig. 14 | Finite element analysis of the SoftFoot Pro. Finite element analysis was conducted according to the two loading conditions defined by the ISO 10328 standard for a static proof test of an ankle-foot device, respectively the heel and the forefoot loading. The loads considered correspond to an occasional severe event that does not affect the functionality of the prosthesis, and they are those for the P5 loading level, i.e. prosthetic users' body mass up to 100 kg. Given the design of the SoftFoot, the heel loading defined in the standard (2240 N) is directly transmitted to the rear arch **(a)**, just as the forefoot loading (2240 N) is primarily transmitted to the frontal arch **(b)**. For this reason, only the rear arch is tested under the heel loading condition **(a)**, and the frontal arch under the forefoot loading condition **(b)**. The loadset defined by the standard is replicated in Creo 8 (PTC, Boston, MA, USA), and results are shown in terms of Von Mises stresses (MPa) in the two foot components for the two loading conditions. In both cases, the stresses measured do not reach the tensile yield strength (σ_y) of the aluminium alloy (AlSi10Mg) used for the rigid components, which is $\sigma_y = 240 \text{ MPa}$.



Supplementary Fig. 15 | Two differently-shaped obstacles. The participants of the two case studies were asked to step on them during two different tasks.

Supplementary Tables

Supplementary Table 1 | Ankle ROM (deg) over the gait cycle (GC) in the sagittal plane. In brackets values of maximum plantarflexion (negative values) and dorsiflexion.

	TASK		
	level		
Case study I: ROM (deg) – GC			
SoftFoot Pro	27.20 (-9.25/+17.95)	25.20 (-4.85/+20.35)	25.30 (-6.15/+19.15)
Triton	22.75 (-7.70/+15.05)	8.35 (-1.31/+7.04)	11.45 (-2.50/+8.95)
sound limb (w/ Triton)	27.51 (-23.58/+3.93)	29.20 (-14.78/+14.42)	21.36 (-10.64/+10.72)
control	26.63 (-13.80/+12.82)	20.13 (-6.77/+13.36)	20.35 (-7.33/+13.02)
Case study II: ROM (deg) – GC			
SoftFoot Pro	20.01 (-5.58/+14.44)	14.40 (-3.61/+10.79)	15.79 (-3.23/+12.56)
sound limb (w/ SoftFoot Pro)	28.17 (-22.18/+6.00)	32.71 (-26.44/+6.27)	36.02 (-30.73/+5.29)
Triton	19.57 (-5.17/+14.40)	10.80 (-1.72/+9.07)	10.38 (-0.96/+9.42)
sound limb (w/ Triton)	41.01 (-35.58/+5.43)	42.92 (-37.45/+5.47)	42.39 (-34.84/+7.55)

Supplementary Table 2 | Maximum plantarflexion and dorsiflexion angles (deg) during and before push-off respectively.

	TASK		
	level		
Case study I: angle peaks (deg) – during/before PUSH-OFF			
SoftFoot Pro	-3.78/+17.95	-4.85/+20.35	-6.15/+19.15
Triton	+0.67/+15.05	+1.40/+7.04	+1.05/+8.95
sound limb (w/ Triton)	-23.58/3.93	-14.78/+11.22	-10.64/+4.52
control	-13.80/+12.82	-6.77/+13.36	-7.33/+13.02
Case study II: angle peaks (deg) – during/before PUSH-OFF			
SoftFoot Pro	-3.70/+14.44	-3.61/+10.79	-3.23/+12.56
sound limb (w/ SoftFoot Pro)	-22.18/+6.00	-26.45/+6.27	-30.73/+5.29
Triton	-0.14/+14.40	+0.60/+9.07	+1.55/+9.42
sound limb (w/ Triton)	-35.58/+5.43	-37.45/+5.47	-34.84/7.55

Supplementary Table 3 | Ankle mean sagittal torque (Nm/kg) and power (W/kg) during the stance phase of walking. Torque and power are normalized by participant's body mass.

	TASK					
	level			level		
Case study I	MEAN torque (Nm/kg) - STANCE			MEAN power (W/kg) - STANCE		
SoftFoot Pro	0.08	0.32	0.24	0.08	-0.05	0.03
Triton	0.36	0.40	0.43	-0.20	-0.06	-0.09
sound limb (w/ Triton)	0.84	0.70	0.67	0.24	0.19	0.11
control	0.65	0.70	0.67	0.23	0.09	0.08
Case study II	MEAN torque (Nm/kg) - STANCE			MEAN power (W/kg) - STANCE		
SoftFoot Pro	0.59	0.64	0.85	-0.02	-0.03	-0.04
sound limb (w/ SoftFoot Pro)	0.55	0.70	0.70	0.20	0.18	0.26
Triton	0.56	0.61	0.54	-0.01	0.00	-0.02
sound limb (w/ Triton)	0.52	0.63	0.64	0.35	0.42	0.47

Supplementary Table 4 | Ankle maximum sagittal torque (Nm/kg) and power (W/kg) over the gait cycle (GC). Torque and power are normalized by participant's body mass.

	TASK					
	level			level		
Case study I	MAX torque (Nm/kg) - GC			MAX power (W/kg) - GC		
SoftFoot Pro	1.29	0.82	0.95	0.44	0.91	0.77
Triton	1.33	0.79	0.96	1.88	0.26	0.58
sound limb (w/ Triton)	1.89	1.33	1.27	4.36	2.22	1.28
control	1.65	1.29	1.34	3.27	1.67	1.84
Case study II	MAX torque (Nm/kg) - GC			MAX power (W/kg) - GC		
SoftFoot Pro	1.70	1.27	1.37	0.54	0.42	0.61
sound limb (w/ SoftFoot Pro)	1.53	1.59	1.60	2.45	3.04	3.09
Triton	1.44	1.02	0.94	1.65	0.51	0.43
sound limb (w/ Triton)	1.67	1.89	1.84	4.04	4.75	4.72

Supplementary Table 5 | Case study II: peaks values (F_1 , F_2 , %BW) of the three ground reaction force (GRF) components for the prosthetic user, in the prosthetic and the contralateral sound limb when using the two prostheses (Triton and SoftFoot Pro), and for able bodied subjects.

	level									
	Triton				SoftFoot				control	
	prosthetic limb		contralateral limb		prosthetic limb		contralateral limb		-	
	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
vGRF	104.67	101.41	137.29	115.19	91.65	116.00	130.14	107.11	101.12	113.58
mIGRF	6.06	4.18	10.70	7.39	6.62	7.62	9.47	7.80	7.30	7.93
apGRF	-9.05	21.98	-25.78	26.79	-6.04	11.00	-13.32	19.62	-15.96	18.89
										
	Triton				SoftFoot				control	
	prosthetic limb		contralateral limb		prosthetic limb		contralateral limb		-	
	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
vGRF	87.57	91.23	183.67	120.33	84.11	97.47	147.07	109.94	104.28	104.07
mIGRF	7.65	6.39	12.04	6.26	5.26	7.41	15.62	7.00	8.25	8.03
apGRF	-20.21	26.54	-39.51	34.59	-6.93	18.80	-22.88	21.34	-16.10	18.96
										
	Triton				SoftFoot				control	
	prosthetic limb		contralateral limb		prosthetic limb		contralateral limb		-	
	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
vGRF	90.82	92.06	172.86	121.22	90.17	93.12	143.53	112.18	100.33	106.02
mIGRF	7.84	7.04	13.00	6.63	6.84	7.03	14.53	7.23	7.78	8.50
apGRF	-13.87	22.18	-38.52	34.31	-12.42	19.19	-17.76	25.25	-15.43	19.48

Supplementary Table 6 | Case study II: symmetry index (SI, %) between the peaks (F_1 , F_2) of the three GRF components in the prosthetic and the contralateral limb when using the two prostheses (Triton and SoftFoot Pro). Lower values indicate greater gait symmetry between limbs.

	level											
	Triton		SoftFoot		Triton		SoftFoot		Triton		SoftFoot	
	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
vGRF	26.97	12.72	34.71	-7.96	70.86	27.52	54.48	12.02	62.22	27.35	45.66	18.56
mIGRF	55.37	55.47	35.46	2.34	44.63	-2.06	99.19	-5.68	49.58	-5.95	71.92	2.83
apGRF	96.09	19.74	75.30	56.33	64.65	26.33	106.97	12.64	94.08	42.95	35.44	27.29

Supplementary Table 7 | Knee mean sagittal angle (deg) until the onset of push-off, and in brackets sagittal ROM (deg) over the gait cycle (GC).

TASK			
	level		
Case study I: MEAN angle (deg) – until push-off (ROM (deg) – GC)			
SoftFoot Pro	3.55 (63.82)	3.30 (65.44)	3.30 (65.49)
Triton	1.10 (68.29)	1.95 (60.14)	1.10 (64.52)
sound limb (w/ Triton)	10.90 (61.31)	16.90 (59.85)	15.30 (55.01)
control	7.43 (48.32)	12.27 (48.52)	11.49 (49.16)
Case study II: MEAN angle (deg) – until push-off (ROM (deg) – GC)			
SoftFoot Pro	26.10 (59.57)	32.16 (61.10)	29.75 (59.57)
sound limb (w/ SoftFoot Pro)	19.70 (62.48)	22.32 (66.55)	21.20 (65.42)
Triton	15.90 (67.71)	23.01 (69.45)	16.86 (70.60)
sound limb (w/ Triton)	23.90 (67.64)	28.80 (68.83)	29.59 (65.97)

Supplementary Table 8 | Knee mean sagittal torque (Nm/kg) and power (W/kg) during the stance phase of walking. Torque and power are normalized by participant's body mass.

TASK						
	level			level		
Case study I	MEAN torque (Nm/kg) - STANCE			MEAN power (W/kg) - STANCE		
SoftFoot Pro	-0.01	-0.17	-0.12	-0.09	-0.23	-0.20
Triton	-0.18	-0.32	-0.30	-0.10	-0.20	-0.22
sound limb (w/ Triton)	-0.17	0.02	0.01	-0.11	-0.29	-0.21
control	0.02	0.13	0.09	-0.04	-0.14	-0.12
Case study II	MEAN torque (Nm/kg) - STANCE			MEAN power (W/kg) - STANCE		
SoftFoot Pro	0.36	0.33	0.27	-0.09	-0.02	-0.06
sound limb (w/ SoftFoot Pro)	0.40	0.53	0.48	-0.18	-0.31	-0.28
Triton	0.26	0.17	0.12	-0.16	-0.10	-0.10
sound limb (w/ Triton)	0.57	0.81	0.79	-0.26	-0.46	-0.50

Supplementary Table 9 | Knee maximum flexor and extensor torque (Nm/kg) in the sagittal plane during the stance phase of walking. Torques are normalized by participant's body mass.

TASK			
	level		
Case study I: MAX FLEXOR torque (Nm/kg) - STANCE			
SoftFoot Pro	-0.28	-0.47	-0.43
Triton	-0.46	-0.83	-0.63
sound limb (w/ Triton)	-0.44	-0.25	-0.28
control	-0.31	-0.09	-0.18
Case study II: MAX EXTENSOR torque (Nm/kg) - STANCE			
SoftFoot Pro	0.56	0.54	0.39
sound limb (w/ SoftFoot Pro)	1.15	1.75	1.60
Triton	0.51	0.37	0.26
sound limb (w/ Triton)	1.65	2.82	2.64
control	0.41	0.44	0.48

Supplementary Table 10 | Hip ROM (deg) in the sagittal plane over the gait cycle (GC).

TASK			
	level		
Case study I: ROM (deg) – GC			
SoftFoot Pro	42.28	41.47	43.32
Triton	44.10	47.54	46.08
sound limb (w/ Triton)	44.19	41.74	42.44
control	41.08	42.55	43.68
Case study II: ROM (deg) – GC			
SoftFoot Pro	36.47	42.81	37.63
sound limb (w/ SoftFoot Pro)	34.81	36.39	36.16
Triton	53.03	50.36	54.35
sound limb (w/ Triton)	43.98	52.54	49.50

Supplementary Table 11 | Hip mean sagittal torque (Nm/kg) and power (W/kg) during the stance phase of walking. Torque and power are normalized by participant's body mass.

	TASK					
	level			level		
Case study I	MEAN torque (Nm/kg) - STANCE			MEAN power (W/kg) STANCE		
SoftFoot Pro	0.12	0.16	0.16	0.37	0.62	0.51
Triton	0.09	0.34	0.22	0.52	0.75	0.68
sound limb (w/ Triton)	0.07	0.13	0.14	0.30	0.38	0.29
control	-0.07	-0.11	-0.08	0.02	-0.05	-0.01
Case study II	MEAN torque (Nm/kg) - STANCE			MEAN power (W/kg) - STANCE		
SoftFoot Pro	0.02	0.06	0.04	0.15	0.17	0.18
sound limb (w/ SoftFoot Pro)	-0.07	-0.11	-0.10	0.15	0.12	0.12
Triton	-0.19	0.00	-0.05	0.15	0.24	0.24
sound limb (w/ Triton)	-0.16	-0.11	-0.12	0.12	0.06	0.13

Supplementary Table 12 | Root Mean Square Error (RMSE) comparing mean plantar pressure distribution of the SoftFoot Pro and a carbon fiber prosthetic foot (VariFlex by Össur) against the human foot during level walking and rectangular obstacle stepping. For level walking, mean pressure values represents an average of 8 strides; for obstacle stepping, values derive from a single stride with the right foot on the obstacle.

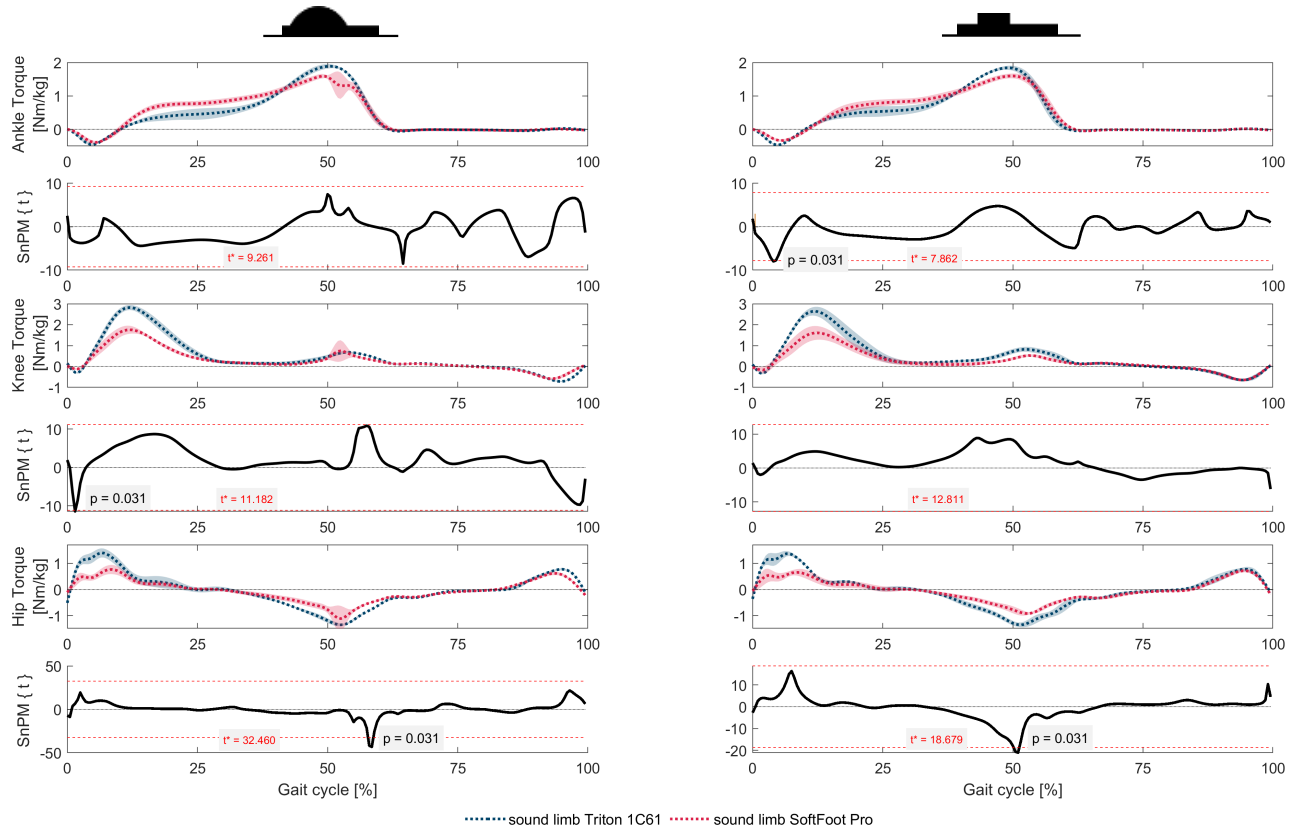
Condition	RMSE	RMSE	RMSE
	Prosthesis on flat ground vs. human on flat ground	Prosthesis on obs vs. human on obs	Prosthesis on obs vs. human on flat ground
Control (human foot)	0	0	0.33*
VariFlex	0.29	0.50	0.62
SoftFoot Pro	0.59	0.47	0.51

*RMSE between the human foot on obstacle and on flat ground.

Supplementary Note 1 | Results of Statistical Analysis

Despite the limited sample size, an inferential statistical analysis was performed to compare the torques of the contralateral joints in the participant of case study II when using the Triton and the SoftFoot Pro on the two obstacles. Data were found to be non-normally distributed according to the Kolmogorov-Smirnov test. Thus, a non-parametric paired two-tailed t -test was performed ($\alpha = 0.05$) using the open-source Statistical Parametric Mapping (SPM) SPM1d code (vM.O.4.12, www.spm1d.org) in Matlab. The statistical *non*-parametric mapping $SnPM\{t\}$ and the null hypothesis rejection threshold (t^*) at each point of the gait cycle were generated and are reported in **Supplementary Fig. 16**. Whenever the $SnPM\{t\}$ crossed the critical threshold, this indicated a statistically significant difference between the two torque patterns ($p < 0.05$).

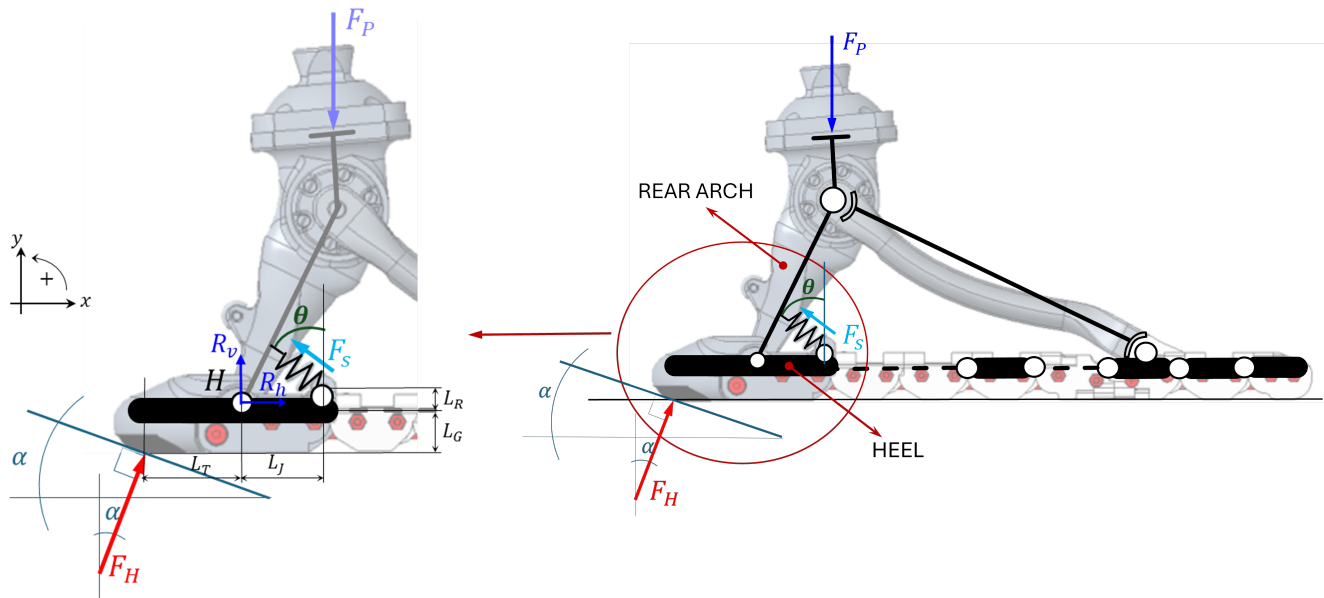
Contralateral limb differences in ankle torque with the two prostheses were statistically significant during load acceptance on the rectangular obstacle ($p = 0.031$). When stepping on the arched obstacle, the difference in contralateral limb knee torques between the two prostheses at stance onset was statistically significant ($p = 0.031$), despite the small sample size. The $SnPM\{t\}$ was also near the rejection threshold around 15% - 20% of the gait cycle and during push-off, i.e. when the two extensor peaks occurred. The SoftFoot significantly reduced the contralateral hip flexor torque during push-off on both obstacles ($p = 0.031$).



Supplementary Fig. 16: Case study II: sagittal ankle, knee, and hip torque (from top to bottom) in the contralateral sound limb when the prosthetic limb steps on the arch-shaped (left column) and the rectangular (right column) obstacles. Mean values across 5 strides ($n=5$) are reported for the contralateral limb when using the Triton (blue dotted line, ± 1 SD) or the SoftFoot Pro (red dotted line, ± 1 SD). A non-parametric paired two-tailed t -test ($\alpha = 0.05$) was performed to compare contralateral torques: the generated $SnPM\{t\}$ statistics (black solid line) and the critical threshold (t^* , horizontal red dotted line) are shown. Where the $SnPM\{t\}$ statistics exceed the critical threshold, the corresponding p -value is reported. Data are normalized to stride duration, the torque by the participant's body mass.

Supplementary Note 2 | Heel Springs Sizing

The springs connecting the rearmost small rigid bodies of the sole to the rear arch through steel pins (**Supplementary Fig. 17**, **Fig. 2** in the main text, **Extended Data Fig. 1**) were sized to prevent foot sole slapping at heel strike, ensuring a smooth loading response phase while withstanding the load acting on the heel in that phase. Specifically, we considered a 2065 N load acting at the heel, as defined by the ISO 10328 standard for static proof testing of ankle-foot devices and a P4 loading level (body mass up to 80 *kg*). Based on the geometry of the links (**Supplementary Fig. 17**), the force transmitted to the springs was calculated using static equilibrium principles, and subsequently their required stiffness was determined.



Supplementary Fig. 17: On the right, schematic of the SoftFoot Pro: the weight of the prosthetic user ($\mathbf{F}_P$ in blue), the spring force ($\mathbf{F}_s$ in light blue, acting at an angle θ with respect to the vertical), and the force acting on the heel ($\mathbf{F}_H$ in red, acting at an angle α with respect to the vertical as defined by the ISO 10328) are shown. On the left, a magnified view shows the *heel* (comprising the heel component and the 1st small body of each of the 5 parallel modules of the sole - they can be considered as a single body, the *heel*, owing to their rigid connection) represented by a black segment. $\mathbf{R}_v$ and $\mathbf{R}_h$ are the constraint forces at the joint connecting the rear arch to the heel.

Since the heel component is rigidly connected to the rearmost small rigid bodies of the sole via steel pins, these elements can be treated as a single body, which will be referred to hereafter as *heel*. Point H represents the joint at which the rear arch of the foot connects to the heel through a steel pin. The torque balance of the heel around H yields

$$F_s = F_H \frac{(\cos \alpha L_T - \sin \alpha L_G)}{(\cos \theta L_J + \sin \theta L_R)}.$$

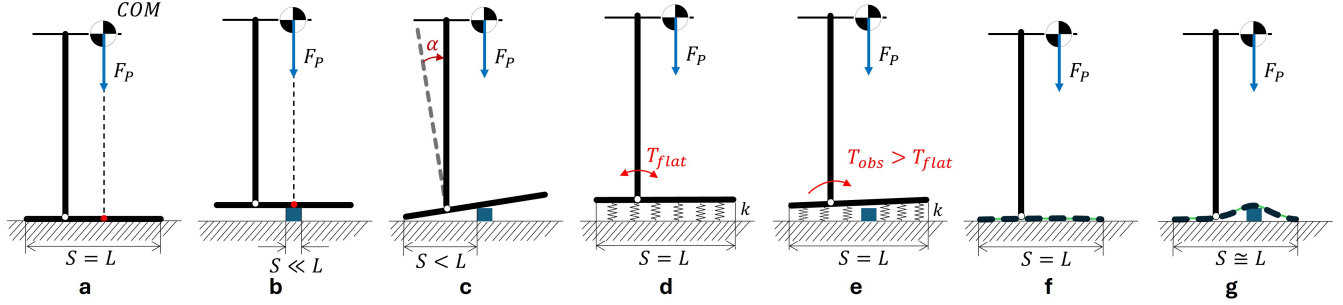
$L_T, L_J, L_G, L_R, \theta$ are design parameters of the considered small body of the sole (**Supplementary Fig. 17**): $L_T = 27\text{ mm}$, $L_J = 32\text{ mm}$, $L_G = 14\text{ mm}$, $L_R = 7\text{ mm}$, $\theta = 45^\circ$. The angle α is defined in section 10.5.2 of the ISO 10328 standard for testing on ankle-foot devices and foot units: $\alpha = 15^\circ$. Given $F_H = 2065\text{ N}$, the resulting magnitude of the spring force is $F_s = 1682\text{ N}$. Considering as initial and final spring lengths those allowed by the geometry of the design, i.e. $L_{\text{springfin}} = 42\text{ mm}$ and $L_{\text{spring0}} = 25\text{ mm}$, a suitable stiffness constant for the heel spring is evaluated as

$$k_{\text{tot}} = F_s / (L_{\text{spring}_{\text{fin}}} - L_{\text{spring}_0}) = 98.9 \text{ N mm}^{-1}.$$

After evaluating commercially available springs, two coil springs in parallel were selected to achieve the total spring stiffness k_{tot} , each having a spring constant of approximately 40 N mm^{-1} (music wire, T100.200.0296.A by Vanel). They represent a close enough approximation of the desired stiffness to allow the desired functionality (considering also the significant safety factor in the ISO standard loads), and are readily available from vendors.

Supplementary Note 3 | Mathematical Model

Artificial feet with adaptive soles, such as the SoftFoot Pro, outperform both flat rigid and fully compliant sole designs on unstructured terrains by maximizing the base of support while avoiding compensatory mechanisms at the ankle joint (Supplementary Fig. 13).



Supplementary Fig. 18: (a) On flat terrain, an artificial foot with a rigid flat sole enables a uniform pressure distribution across the support length (S), which coincides with the entire foot length (L). The vertical projection of the center of mass (COM) must fall within S to ensure stability. When negotiating obstacles, preserving balance requires either (b) having the COM projection within the substantially reduced support length, or (c) applying a compensation at the ankle joint (α) to counteract the foot rotation induced by the obstacle, mitigating the reduction of the support length. (d-e) Artificial feet with a compliant flat sole (represented by springs - stiffness k - placed between the rigid foot part and the ground): the compliant sole allows absorption of the small obstacles, without ankle compensations and support length decrease. However, tilting is introduced both on flat ground and on the obstacle, which requires ankle compensation (see ankle torques T_{flat} and T_{obs}). (f) Artificial foot with an adaptive sole that conforms to the ground profile, providing an extended support length, and avoiding both tilting and ankle compensation in case of obstacles (g). F_P = body weight.

The mathematical model of the SoftFoot Pro describing its behaviour when statically balancing is derived below. We refer to the rigid bodies defined in Supplementary Fig. 19.

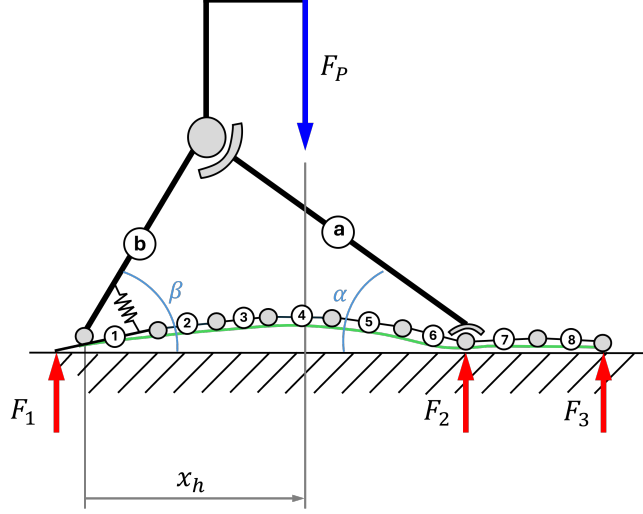
The variable $\mathbf{q} = [q_1 \dots q_{n+2}] \in \mathbb{R}^{n+2}$ collects the configuration of the foot sole and phalanges ($n = 6$, see also $q_i \forall i \in \{1, \dots, n+2\}$ in Supplementary Fig. 20). Given the user's weight F_P on the foot, and the three ground reaction forces F_1, F_2, F_3 , imposing the force and torque equilibria of the foot as a whole yields

$$\begin{aligned} F_P &= F_1 + F_2 + F_3 \\ F_P &= \frac{aC_\alpha + bC_\beta + L_{heel}C_1}{x_h + L_{heel}C_1} F_2 + \frac{aC_\alpha + bC_\beta + L_{heel}C_1 + L_{n+1}C_{n+1} + L_{n+2}C_{n+2}}{x_h + L_{heel}C_1} F_3 \end{aligned} \quad (1)$$

where x_h is the horizontal distance between the F_P application point and the joint between link 1 and the rear arch; L_{heel} denotes the part of L_1 (i.e. the length of link 1) extending from the posterior extremity of the calcaneus (point of application of force F_1) to the joint between link 1 and the rear arch; L_{n+1} and L_{n+2} are the length of respectively the $(n+1)^{th} = 7^{th}$ and $(n+2)^{th} = 8^{th}$ links; a, b are respectively the length of the frontal and rear arches; α, β are the angles between the two arches and the ground (Supplementary Figs. 19 and 20); and $F_P, F_1, F_2, F_3 \in \mathbb{R}$. For the sake of compactness, $C_\alpha = \cos(\alpha)$, $C_\beta = \cos(\beta)$, $C_1 = \cos(q_1)$, $C_{n+1} = \cos(\sum_{j=1}^{n+1} q_j)$, $C_{n+2} = \cos(\sum_{j=1}^{n+2} q_j)$.

By balancing the forces along x for the rigid bodies of the foot (Supplementary Fig. 20), we obtain

$$\begin{aligned} R_M C_\alpha &= -R_0^x \\ R_1^x &= R_0^x \\ R_i^x &= R_{i+1}^x \quad \forall i \in \{1, \dots, n-2\} \\ R_{n-1}^x &= R_n^x - R_M C_\alpha \\ R_n^x &= R_{n+1}^x \\ R_{n+1}^x &= 0 \end{aligned} \quad (2)$$



Supplementary Fig. 19: Simplified schematic of the SoftFoot Pro showing its main components under static loading. a, b are respectively the frontal and rear arches. F_P represents the user's weight (the user's prosthetic limb is rigidly connected to the rear arch (b)). F_1, F_2, F_3 are the three considered contact forces. Links 7 – 8 represent the phalanges. The plantar fascia is implemented by a set of $n = 6$ links (links 1 – 6), and a tendon (in green) that runs from the calcaneus to the tip of the toe. Links 1 – 8 are connected to each other through elastic bands of stiffness e_i . The rear arch (b) and the 1st link are connected through a spring of stiffness e_0 .

where R_i^x is the horizontal reaction force exerted on the $(i + 1)^{th}$ link by the $(i)^{th}$ link. R_0^x and $R_M C_\alpha$ are the horizontal reaction forces due to the interaction with the main structure of the foot. Some algebraic manipulations allow to transform (2) in

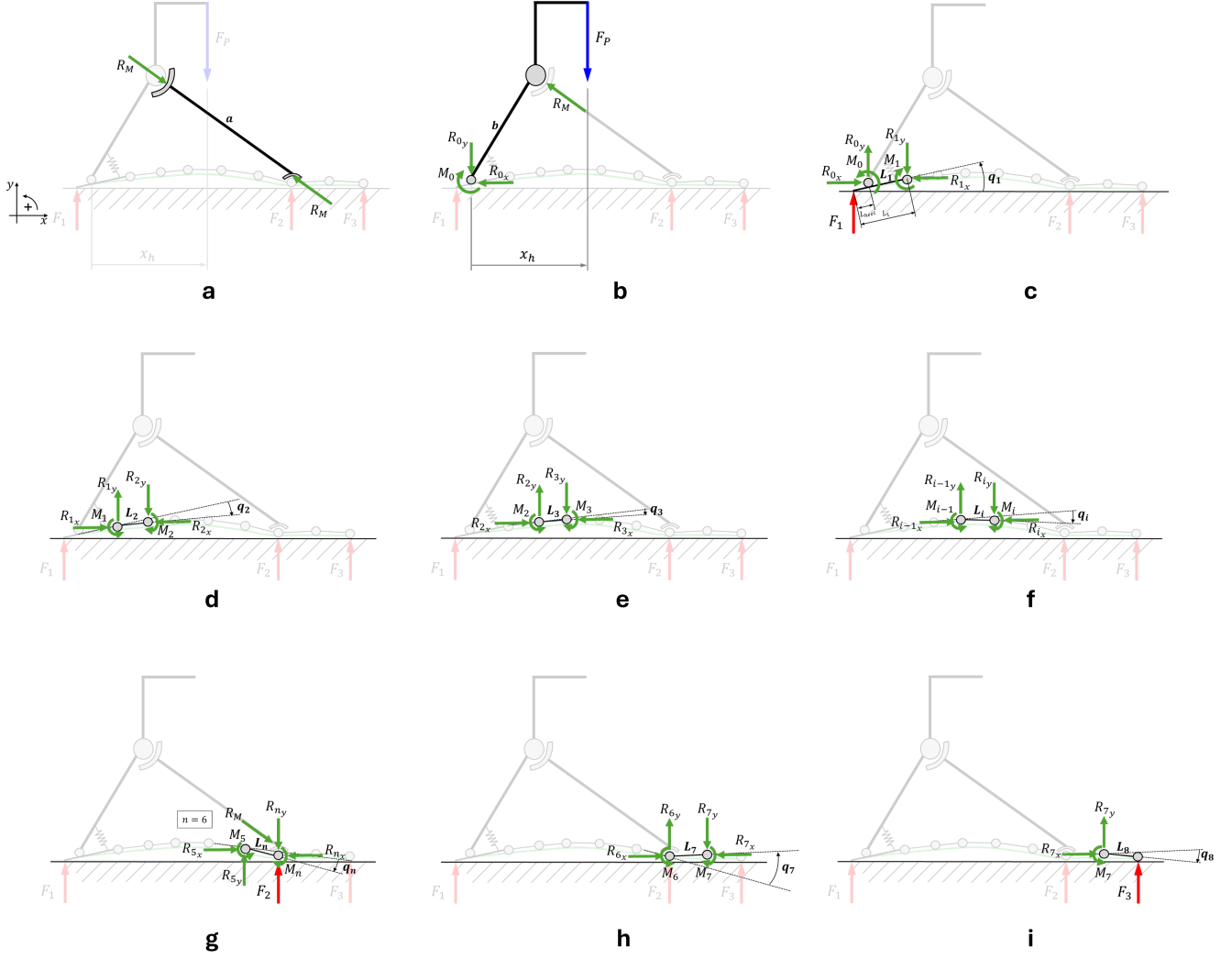
$$\begin{aligned} R_0^x &= -R_M C_\alpha \\ R_i^x &= -R_M C_\alpha \quad \forall i \in \{1, \dots, n-1\} \\ R_n^x &= R_{n+1}^x = 0. \end{aligned} \quad (3)$$

Similarly, the force balance along y leads to

$$\begin{aligned} R_M S_\alpha - F_1 - F_2 - F_3 &= R_0^y \\ R_1^y &= F_1 + R_0^y = R_M S_\alpha - F_2 - F_3 \\ R_i^y &= R_{i+1}^y \quad \forall i \in \{1, \dots, n-2\} \\ R_{n-1}^y &= R_n^y + R_M S_\alpha - F_2 \\ R_n^y &= R_{n+1}^y \\ R_{n+1}^y &= -F_3 \end{aligned} \quad (4)$$

where R_i^y is the vertical reaction force exerted on the $(i + 1)^{th}$ link by the i^{th} link; R_0^y and $R_M S_\alpha$ are the vertical reaction forces due to the interaction with the structure; $S_\alpha = \sin(\alpha)$. By solving it, it yields

$$\begin{aligned} R_0^y &= R_M S_\alpha - F_1 - F_2 - F_3 \\ R_i^y &= R_M S_\alpha - F_2 - F_3 \quad \forall i \in \{1, \dots, n-1\} \\ R_n^y &= R_{n+1}^y = -F_3. \end{aligned} \quad (5)$$



Supplementary Fig. 20: Free body diagrams for the (a) frontal arch, (b) the rear arch, (c)-(g) the $n = 6$ sole bodies included between the heel and the metatarsophalangeal joints, and (h)-(i) the two toe phalanxes of the SoftFoot Pro. For each one of those components, reaction forces ($\mathbf{R}_M, \mathbf{R}_0, \mathbf{R}_i \forall i \in \{1, \dots, n-1\}, \mathbf{R}_n, \mathbf{R}_{n+1}, \mathbf{R}_{n+2}$), moments ($M_0, M_i \forall i \in \{1, \dots, n-1\}, M_n, M_{n+1}, M_{n+2}$), and external forces ($\mathbf{F}_1, \mathbf{F}_2, \mathbf{F}_3, \mathbf{F}_P$) are shown. a and b represent the length of the two arches, $L_1 - L_8$ the length of the 8 sole bodies from the heel to the tip of the toes, and $q_1 - q_8$ the angle of each link relative to the previous one, with q_1 measured relative to the ground.

Balancing the torque for the sole bodies (links 1 – 8) leads to

$$\begin{aligned}
 m_0 - m_1 + R_1^x (L_1 - L_{\text{heel}}) S_1 - R_1^y (L_1 - L_{\text{heel}}) C_1 - F_1 L_{\text{heel}} C_1 &= 0 \\
 m_i - m_{i+1} + R_{i+1}^x L_{i+1} S_{i+1} - R_{i+1}^y L_{i+1} C_{i+1} &= 0 \quad \forall i \in \{1, \dots, n-2\} \\
 m_{n-1} - m_n + R_n^x L_n S_n - R_n^y L_n C_n &= 0 \\
 m_n - m_{n+1} + R_{n+1}^x L_{n+1} S_{n+1} - R_{n+1}^y L_{n+1} C_{n+1} &= 0 \\
 m_{n+1} &= -F_3 L_{n+2} C_{n+2}
 \end{aligned} \tag{6}$$

where m_i is the torque exerted on the $(i+1)^{\text{th}}$ link; $S_1 = \sin(q_1)$; $S_{i+1} = \sin(\sum_{j=1}^{i+1} q_j)$ and $C_{i+1} = \cos(\sum_{j=1}^{i+1} q_j)$; $S_n = \sin(\sum_{j=1}^n q_j)$ and $C_n = \cos(\sum_{j=1}^n q_j)$; $S_{n+1} = \sin(\sum_{j=1}^{n+1} q_j)$ and $C_{n+1} = \cos(\sum_{j=1}^{n+1} q_j)$; $C_{n+2} = \cos(\sum_{j=1}^{n+2} q_j)$; $L_{i+1} - L_n$ represent the length of the sole bodies included between the heel and the metatarsophalangeal joints, L_{n+1} and L_{n+2}

the length of the phalanxes of the toe (links 7 and 8 in **Supplementary Fig. 19**). By replacing (3) and (5) in (6), we obtain

$$\begin{aligned} m_0 - m_1 &= R_M C_\alpha (L_1 - L_{\text{heel}}) S_1 + (R_M S_\alpha - F_2 - F_3)(L_1 - L_{\text{heel}}) C_1 + F_1 L_{\text{heel}} C_1 \\ m_i - m_{i+1} &= R_M C_\alpha L_{i+1} S_{i+1} + (R_M S_\alpha - F_2 - F_3) L_{i+1} C_{i+1} \quad \forall i \in \{1, \dots, n-1\} \\ m_n - m_{n+1} &= -F_3 L_{n+1} C_{n+1} \\ m_{n+1} &= -F_3 L_{n+2} C_{n+2}, \end{aligned} \quad (7)$$

which can be expressed in matrix form as

$$\mathbf{M}_{n+2} \mathbf{m} + \mathbf{A}^x + \mathbf{A}^y = \mathbf{0} \quad (8)$$

where $\mathbf{m} \in \mathbb{R}^{n+2}$ collects the terms m_i . $\mathbf{M}_{n+2} \in \mathbb{R}^{m \times m}$, $\mathbf{A}^x \in \mathbb{R}^{n+2}$, and $\mathbf{A}^y \in \mathbb{R}^{n+2}$ are defined as

$$\mathbf{M}_{n+2} = \begin{bmatrix} 1 & -1 & 0 & \cdots & 0 \\ 0 & 1 & -1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 & -1 \\ 0 & \cdots & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{A}^x = \begin{bmatrix} -R_M C_\alpha (L_1 - L_{\text{heel}}) S_1 \\ -R_M C_\alpha L_2 S_2 \\ \vdots \\ -R_M C_\alpha L_n S_n \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{A}^y = \begin{bmatrix} -(R_M S_\alpha - F_2 - F_3)(L_1 - L_{\text{heel}}) C_1 - F_1 L_{\text{heel}} C_1 \\ -(R_M S_\alpha - F_2 - F_3) L_2 C_2 \\ \vdots \\ -(R_M S_\alpha - F_2 - F_3) L_n C_n \\ F_3 L_{n+1} C_{n+1} \\ F_3 L_{n+2} C_{n+2} \end{bmatrix}. \quad (9)$$

The torque $\mathbf{m}$ is due to elastic effects and tendon coupling, and can be explicitly evaluated to be $\forall i \in \{1, \dots, n+1\}$

$$m_0 = -e_0(q_1 - \beta) + r_0 T, \quad m_i = -e_i q_{i+1} + r_i T \quad (10)$$

where e_0 is the stiffness of the spring connecting link 1 to the rear arch; e_i and r_i are respectively the elastic constant of the elastic bands and the transmission ratio (i.e., the pulley radius) acting on the i^{th} joint; T is the tendon tension; β represents the pretension of the first spring. Equation (10) can be expressed in matrix form as

$$\mathbf{m} = -\mathbf{E} \mathbf{q} + \mathbf{e}_E \beta + \mathbf{p}^T T \quad (11)$$

where $\mathbf{e}_E = [e_0 \ 0 \ \cdots \ 0]^T \in \mathbb{R}^{n+2}$ maps the effect of the spring connecting link 1 to the rear arch, $\mathbf{E} \in \mathbb{R}^{n+2 \times n+2}$ collects all the elastic terms (e_0 of the aforementioned spring and e_i of the elastic bands), $\mathbf{p} = [r_0 \ \cdots \ r_{n+1}] \in \mathbb{R}^{1 \times n+2}$ collects the transmission ratio.

The reaction force R_M from the torque balance in the rear arch can be expressed as

$$\begin{aligned} R_M C_\alpha b S_\beta + R_M S_\alpha b C_\beta &= F_P x_h + m_0 = F_P x_h - e_0(q_1 - \beta) \Rightarrow \\ R_M &= F_P \frac{x_h}{b} \frac{1}{S_{\alpha+\beta}} - \frac{e_0(q_1 - \beta)}{b} \frac{1}{S_{\alpha+\beta}} \end{aligned} \quad (12)$$

where $S_{\alpha+\beta} = \sin(\alpha + \beta) = S_\alpha C_\beta + C_\alpha S_\beta$. By including the constraints imposed by the ground structure $\sum_1^{n+2} L_i S_i = \delta$ and by the tendon $\mathbf{p} \mathbf{q} = \sigma$, where δ is the terrain height, L_i is the length of the i^{th} sole body, $S_i = \sin(\sum_1^i q_j)$, and σ is the tendon length, we can collect (1), (8), and (11) in

$$\begin{aligned} \mathbf{0} &= \mathbf{M}(-\mathbf{E} \mathbf{q} + \mathbf{e}_E \beta + \mathbf{p}^T T) + \mathbf{A}^x + \mathbf{A}^y \\ F_P &= F_1 + F_2 + F_3 \\ F_P &= \frac{a C_\alpha + b C_\beta + L_{\text{heel}} C_1}{x_h + L_{\text{heel}} C_1} F_2 + \frac{a C_\alpha + b C_\beta + L_{\text{heel}} C_1 + L_{n+1} C_{n+1} + L_{n+2} C_{n+2}}{x_h + L_{\text{heel}} C_1} F_3 \\ \sum_1^{n+2} L_i S_i &= \delta \\ \mathbf{p} \mathbf{q} &= \sigma. \end{aligned} \quad (13)$$

This is a set of $n + 6$ ($n = 6$ in the SoftFoot Pro) nonlinear equations, in the $n + 6$ unknowns $\mathbf{q} \in \mathbb{R}^{n+2}$, $F_1, F_2, F_3 \in \mathbb{R}$, and $T \in \mathbb{R}$. By introducing the hypothesis of small angles, i.e. $q_i \simeq 0 \forall i \in \{1, \dots, n + 2\}$, the set of equations (13) can be linearized. Specifically, the small angles hypothesis leads to

$$S_i \simeq \sum_1^i q_j, \quad C_i \simeq 1, \quad \alpha \simeq \bar{\alpha}, \quad \beta \simeq \bar{\beta}, \quad T \simeq 0. \quad (14)$$

By applying these assumptions, it yields

$$\begin{aligned} R_M &\simeq \frac{F_P x_h + e_0 \bar{\beta}}{b S_{\bar{\alpha} + \bar{\beta}}}, \\ \sum_1^{n+2} L_i S_i &\simeq \mathbf{C} \mathbf{q} \quad \text{with} \quad \mathbf{C} = \mathbf{1}_{n+2}^T \mathbf{L}, \quad \mathbf{1}_{n+2} = [1 \dots 1]^T \in \mathbb{R}^{n+2}, \quad \mathbf{L} = \begin{bmatrix} L_1 & 0 & \dots & \dots & 0 \\ L_2 & L_2 & 0 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ L_7 & L_7 & \dots & L_7 & 0 \\ L_8 & L_8 & \dots & L_8 & L_8 \end{bmatrix}, \\ \mathbf{A}^x &\simeq -R_M C_{\bar{\alpha}} \begin{bmatrix} \frac{L_1 - L_{\text{heel}}}{L_1} & 0 & \dots & 0 \\ 0 & I_{n-1 \times n-1} & 0 & \vdots \\ \vdots & \mathbf{0}^T & \vdots & \vdots \\ 0 & \mathbf{0}^T & 0 & 0 \end{bmatrix} \mathbf{L} \mathbf{q}, \\ \mathbf{A}^y &\simeq -\mathbf{e}_R R_M + \mathbf{e}_F \mathbf{F} \quad \text{with} \quad \mathbf{e}_R = S_{\bar{\alpha}} \begin{bmatrix} L_1 - L_{\text{heel}} \\ L_2 \\ \vdots \\ L_6 \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{e}_F = \begin{bmatrix} -L_{\text{heel}} & L_1 - L_{\text{heel}} & L_1 - L_{\text{heel}} \\ \vdots & L_2 & L_2 \\ \vdots & \vdots & \vdots \\ \vdots & L_6 & L_6 \\ 0 & 0 & L_7 \\ 0 & 0 & L_8 \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} F1 \\ F2 \\ F3 \end{bmatrix}. \end{aligned} \quad (15)$$

Consequently, the linear form of equation (13) follows

$$\begin{bmatrix} -\mathbf{B} & [\mathbf{p}^T & \mathbf{d}] \\ \begin{bmatrix} \mathbf{p} \\ \mathbf{C} \end{bmatrix} & \emptyset \end{bmatrix} \begin{bmatrix} \mathbf{q} \\ T \\ \mathbf{F} \end{bmatrix} = \begin{bmatrix} \mathbf{m}_E \\ \sigma \\ \delta \end{bmatrix}, \quad (16)$$

where

$$\begin{aligned} \mathbf{d} &= \mathbf{M}_{n+2}^{-1} \mathbf{e}_F, \\ \mathbf{B} &= \mathbf{E} + \mathbf{M}_{n+2}^{-1} \begin{bmatrix} \frac{L_1 - L_{\text{heel}}}{L_1} & 0 & \dots & 0 \\ 0 & I_{n-1 \times n-1} & 0 & \vdots \\ \vdots & \mathbf{0}^T & \vdots & \vdots \\ 0 & \mathbf{0}^T & 0 & 0 \end{bmatrix} \mathbf{L} \frac{(F_P x_h + e_0 \bar{\beta}) C_{\bar{\alpha}}}{b S_{\bar{\alpha} + \bar{\beta}}}, \\ \mathbf{m}_E &= \mathbf{M}_{n+2}^{-1} \mathbf{e}_R \frac{F_P x_h + e_0 \bar{\beta}}{b S_{\bar{\alpha} + \bar{\beta}}} - \mathbf{e}_E \bar{\beta}. \end{aligned} \quad (17)$$

The set of equations in (16) describes the relationship between the foot configuration $\mathbf{q}$, the ground-contact forces $\mathbf{F}$, and the tendon tension T , as a result of the external forces acting on the foot ($\mathbf{F}_P$, appearing in $\mathbf{B}$ and in $\mathbf{m}_E$), and the constructive parameters of the SoftFoot Pro (geometry a, b, α, β, L_i , elastic terms $\mathbf{e}_E$ and $\mathbf{E}$, and pulley radii $\mathbf{p}$).

This set of equations enabled us to optimize the design parameters for maximum contact area across shapes and forces typical of daily-life activities:

- The sole bodies' length, $L_1 = 60 \text{ mm}$, $L_2 = L_3 = L_4 = L_6 = L_7 = 27 \text{ mm}$, $L_5 = 29 \text{ mm}$, $L_8 = 23 \text{ mm}$, $L_{\text{heel}} = 25 \text{ mm}$.
- The arches' length, $a = 135 \text{ mm}$ and $b = 75 \text{ mm}$.
- The orientation of the two arches with respect to the ground, $\bar{\alpha} = 30^\circ$ and $\bar{\beta} = 60^\circ$.
- The linear stiffness of the elastic bands (natural rubber, radius $r_{\text{eb}} = 1.25 \text{ mm}$, length $L_{\text{eb}} = 10 \text{ mm}$, nominal stiffness of 35 *ShA*) is evaluated first by applying the Gent's relation for Shore A hardness² to evaluate the Young's module, and then by considering their geometry: $k_{\text{eb}} = E_{\text{eb}} \frac{\pi r_{\text{eb}}^2}{L_{\text{eb}}} = 684.77 \text{ N m}^{-1}$, with $E_{\text{eb}} = 1.395 \text{ MPa}$. The corresponding joint stiffness (e_i) is then estimated by considering the two elastic bands acting in parallel at each joint and their torsional stiffness: $e_i = 2k_{\text{eb}}l_{\text{j-eb}}^2 = 2 \times 0.0335 \text{ N m rad}^{-1} = 0.067 \text{ N m rad}^{-1}$, where $l_{\text{j-eb}} = 7 \text{ mm}$ is the perpendicular distance from the joint's axis of rotation to the line of action of the elastic band force.
- The total stiffness of the two springs connecting link L_1 to the rear arch b , $k_{\text{tot}} = 80 \text{ N mm}^{-1}$, as defined in **Supplementary Note 2**, corresponds to the torsional stiffness $e_0 = k_{\text{tot}}L_{\text{J}}^2 = 80 \text{ N mm}^{-1}(32 \text{ mm})^2 = 81.92 \text{ N m rad}^{-1}$ (see L_{J} in **Supplementary Note 2**).
- The pulley radii, $r_0 = 0 \text{ mm}$ and $r_i = 4 \text{ mm} \forall i \in \{1, \dots, n+1\}$.

Supplementary References

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