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Evaluating the Impact of Prosthetics on Gait Symmetry in Unilateral Lower Limb Amputees

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ABSTRACT

Objective Gait symmetry is a primary criterion for assessing the rehabilitation progress of unilateral transtibial amputees with prostheses. This study aimed to examine the gait symmetry of dynamic kinematic and kinetic functions in unilateral transtibial amputees using prostheses during walking.
Methods The study was approved by the University Ethics Committee and involved five (3 females and 2 males) unilateral transtibial amputees (age: (mean $\pm$ SD) 63.4 $\pm$ 7.7 years, height: 165.6 $\pm$ 6.4 cm; body mass: 69.4 $\pm$ 4.1 kg; years of using prosthetic foot: 30.8 $\pm$ 9.3 years). For collecting the kinematic and kinetic data, thirty-nine passive-reflective markers were placed on the participant according to the landmarks set of the plug-in full body model. An 8-camera motion capturing system (VICON, Nexus 2.0 Inc., Oxford, UK) and 2 force plates (AMTI, Advanced Mechanical Technology, Inc., Watertown, USA) mounted under the walkway were recorded 100 frames per second simultaneously. All the systems were calibrated before the experiment. Participants walked at their self-selected walking speeds. Based on their self-selected walking speed record, $\pm$ 10% range were calculated as the references for each participant's fast and slow walking speed. Each participant repeated walking trials until a minimum of 5 "clean" foot force plate contact with both right and left limbs were acquired. The corresponding data from 5 gait cycles were selected to calculate the lower limb joints angles and vertical ground reaction force (GRF) during walk. Then symmetry index (SI) was calculated to provide a descriptive marker for the degree of symmetry between the intact and residual limbs. A value of SI less than 5% reflects good symmetry between the limbs, whereas increasingly positive values indicate the value for the residual limb was greater than that of the intact limb, while negative values denote that the intact limb value was greater.
Results Normalized vertical GRF of two limbs increased with increased walking speeds. The corresponding SI was the largest when heel strike with slow walking speed (6.2 $\pm$ 0.8 m/s). Gait imbalance was observed during loading response and midstance (around 30% - 45% stance phase) when the walking speed was increased. While SI values of ankle angles were enlarged with increased walking speed, indicating more asymmetry of ankle angle between two limbs with their traditional prostheses when the walking speed increases.
Conclusions The current prostheses can only support the basic daily activities for the unilateral transtibial amputees. The new design of prostheses should therefore focus on kinetic and kinematic parameters such as the symmetry between the residual limb and the intact limb, and energy saving for the amputees during high intensity activities.

Keywords: Walking, Balance, Prostheses design, Lower extremity amputation

INTRODUCTION

Walking is a fundamental aspect of daily life. However, individuals who have undergone unilateral lower extremity amputation experience a significant loss of mobility, leading to inconvenience and hardship. Prosthesis use can disguise the partial or complete loss of a lower limb in appearance, while assisting those with a unilateral lower extremity amputation to walk, engage in daily activities, and maintain a degree of physical movement and self-care (Shi et al., 2023b). Gait symmetry is a primary criterion for evaluating the rehabilitation progress of unilateral transtibial amputees using prostheses (Mattes et al., 2000, Winiarski et al., 2021). The Symmetry Index (SI) is a commonly used parameter and is considered clinically sensitive in the study of spatiotemporal gait parameters (Błażkiewicz and Wit, 2012). Compared to a healthy group, noticeable asymmetry can be observed among amputees with unilateral lower extremity loss (Shi et al., 2023a). Long-term asymmetry can lead to degenerative changes in all joints of the healthy lower limb (Nolan, 2009). Previous studies have used scalar indicators and symbol-based characteristics to assess gait symmetry, including gait parameters and ground reaction force (GRF). However, a single measure cannot provide a comprehensive understanding of gait symmetry, as the asymmetries in the angle-time characteristics from which these metrics are derived are not well represented by discrete values. There is limited knowledge about gait symmetry in terms of kinematic and kinetic variables in patients' post-unilateral lower extremity amputation. Therefore, this study aims to use both SI and dynamic symmetry function (SF) parameters to thoroughly assess the symmetric function of unilateral lower limb amputees using their current prosthetics.

Method

To simulate the daily outdoor activities including slow, and fast walking speed for the unilateral residual limb amputees by their own prosthetics, the participants were invited to visit our laboratory for better understanding the functions of their prosthetics for daily usage. Human subject ethics approval was granted by the University Ethics Committee. Five unilateral transtibial amputees (3 females and 2 males) were recruited in this study. Table 1 shows the information of the recruited amputees.

Table 1. Recruited Amputees' information.

Subject No.	1	2	3	4	5	Mean (SD)
Gender	F	F	F	M	M	
Age (years)	64	62	50	69	67	62.4 (7.4)
Body mass (kg)	67.8	50.8	69.8	63.5	75	65.4 (9.1)
Height (cm)	160	148	159	165	174	161.2 (9.5)
Residual limb side	R	R	R	L	R	
Years of using prosthetic foot	40	2	19	40	25	25.2 (15.9)
Prosthetic foot level	K3	K2	K3	K3	K3	
Average daily walking speed (km/h)	3.4	3.5	3.6	3.7	3.8	3.7 (0.4)

Note: F indicates female; M indicates male.

The normalized GRF and kinematic data of lower limb joints were also acquired from motion capturing system (VICON, Nexus 2.0 Inc., Oxford, UK), and 2 force plates (AMTI, Advanced Mechanical Technology, Inc., Watertown, USA) respectively. Thirty-nine passive-reflective markers of 14 mm in diameter were placed on the participant (**Figure 1**) according to the landmarks set of the plug-in full body model (Haddas et al., 2018). An 8-camera motion capturing system (VICON, Nexus 2.0 Inc., Oxford, UK) and 2 force plates (AMTI, Advanced Mechanical Technology, Inc., Watertown, USA) mounted under the walkway were utilized for gait analysis and recorded 100 frames per second simultaneously. All the systems were calibrated before the experiment.

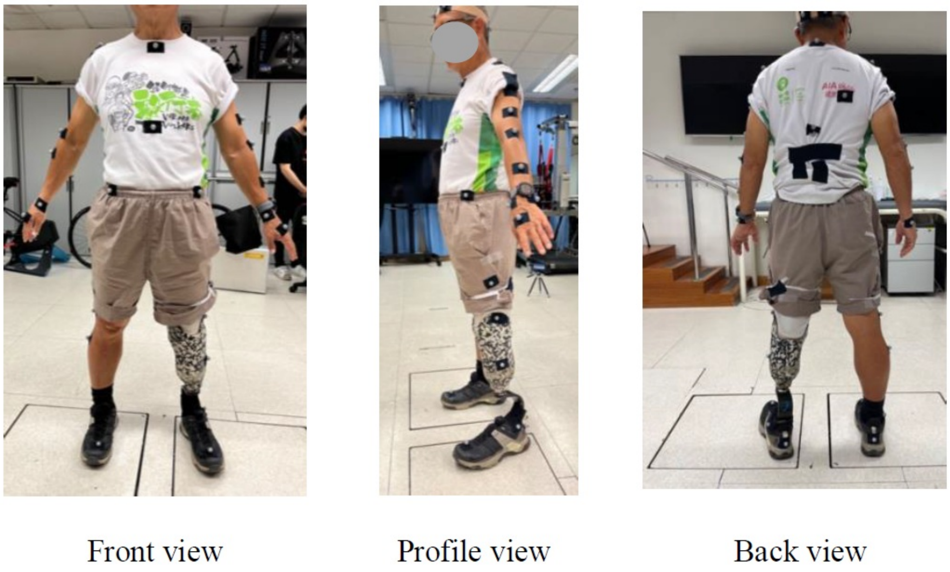

Figure 1: Land markers attached on the participant.

Then the participant walked on the force plate at a self-selected walking speed to perform his/her normal gait (Lu et al., 2015) and the foot would land on the force plate naturally (Sawacha et al., 2009). Their average self-selected walking speed was 3.7 ± 0.4 km/h. Based on their self-selected walking speed record, ± 10% range were calculated as the references for each participant's fast and slow walking speed. Their averaged fast and slow walking speed were 4.1 ± 0.5 km/h, and 3.4 ± 0.4 km/h respectively. Each participant repeated walking trials until a minimum of 5 "clean" foot force plate contact with both right and left limbs were acquired (Petrovic et al., 2018, Švehlík et al., 2009). The corresponding data from 5 gait cycles were selected to calculate the angles of lower limb joints and generated GRF during (**Figure 2**).

SI was calculated to provide a descriptive marker for the degree of symmetry between the intact (I) and residual (R) limbs (see **Figure 3**) for normalized GRF by using *Equation (1)* below (Herzog et al., 1989, Winiarski et al., 2021).

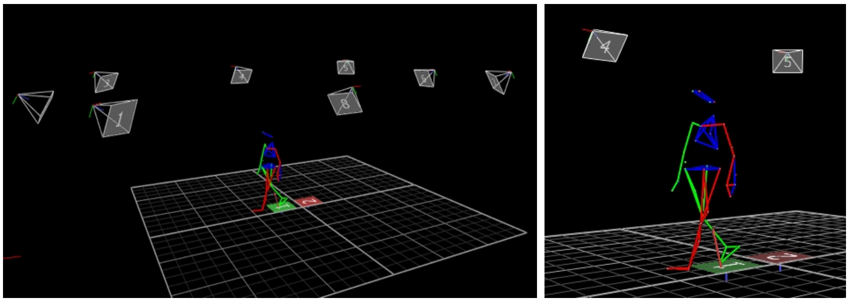

Figure 2: Amputee's walking tracked in the Motion capture system.

$$SI\% = \frac{(R - I)}{0.5\ (R + I)} * 100 \quad (1)$$

Figure 3: Intact limb and residual limb.

However, due to the artificial extreme values occur in the region of zero-crossings, SI% is not suitable for the analysis of joint angles (Siebers et al., 2021, Herzog et al., 1989). To investigate the symmetry of joint angles, the dynamic SF was proposed to provide information on the symmetry in the entire range of motion (t) of lower limb joints by using *Equation 2* (Winiarski et al., 2021). All individual gait cycles were averaged first within and then between subjects for the intact and residual limb separately.

$$SF(t)\% = 2 * \frac{R(t) - I(t)}{Range\ R(t) + Range\ I(t)} * 100 \quad (2)$$

A value of SI or SF less than 5% reflects good symmetry between the limbs, whereas increasingly positive or negative values indicate increasing asymmetry for a variable in question (Herzog et al., 1989, Forczek and Staszkiewicz, 2012, Sadeghi et al., 2000). In addition, positive values indicate the value for the residual limb was greater than that of the intact limb, while negative values denote that the intact limb value was greater (Winiarski et al., 2019).

Kinetic symmetry analysis. Figure 4 shows that the normalized GRFs of two limbs were increased with increased walking speeds. The corresponding SI area was the largest during heel strike with slow walking speed (6.2 ± 0.8 m/s). Gait imbalance was observed during loading response and midstance (around 30%–45% stance phase) when the walking speed was increased. **Table 2** shows that the maximum values of normalized GRF were higher by the intact limb than the values by the residual limb with three walking speeds. The corresponding negative value of SI reflects the values of intact limb were greater in most of stance phase, while the values of residual limb were greater at toe-off.

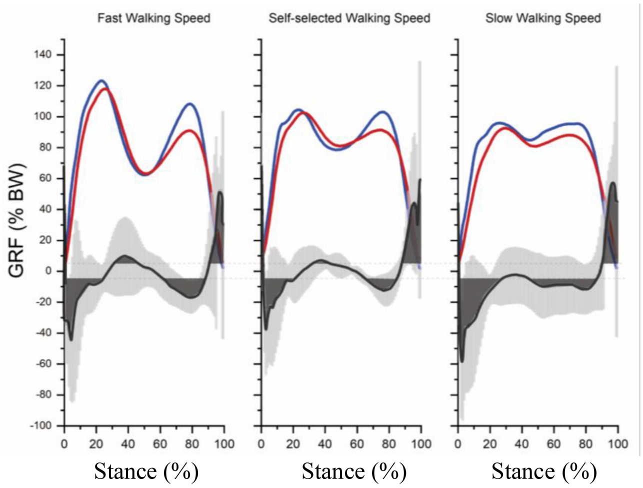

Figure 4: The mean of normalized GRF (% body weight (BW)) and the corresponding SI (%) (solid dark line) during stance with different walking speeds. ***Blue*** *and* ***red*** *solid lines indicate the normalized GRF of intact limb and residual limb respectively.* ***Dark*** *solid line indicates SI (%) of two limb sides.* ***Light grey*** *area shows the standard deviations of SI.* ***Dark grey*** *area indicates the SI are more than 5%.*

Table 2. Mean and ± standard deviation (SD) for the normalized ground reaction force and the corresponding SI%.

		Intact	Residual	SI%
Fast Walking Speed	$Peak_{min}$ (%BW)	1.3 (0.6)	1.8 (1.0)	30.7 (71.8)
	t_{min} (%CT)	34.0 (23.3)	67.1 (23.3)	83.6 (68.7)
	$Peak_{max}$ (%BW)	130.8 (8.2)	121.3 (12.7)	−7.8 (7.0)
	t_{max} (%CT)	31.3 (17.4)	26.4 (3.3)	−5.3 (53.2)
	ROM over gait cycle	129.5 (8.1)	119.5 (13.0)	−8.4 (7.3)
Self-selected Waking Speed	$Peak_{min}$ (%BW)	1.3 (0.8)	2.3 (0.6)	68.5 (46.3)
	t_{min} (%CT)	40.6 (14.8)	73.5 (27.5)	53.7 (36.5)
	$Peak_{max}$ (%BW)	115.0 (14.0)	109.9 (10.9)	−4.4 (11.7)
	t_{max} (%CT)	38.8 (18.4)	25.5 (5.2)	−31.2 (42.7)
	ROM over gait cycle	113.8 (14.3)	107.6 (11.1)	−5.4 (12.1)

(Continued)

Table 2. Continued

		Intact	Residual	SI%
Slow Waking Speed	$Peak_{min}$ (%BW)	1.5 (0.6)	1.7 (0.2)	16.5 (42.8)
	t_{min} (%CT)	47.2 (18.1)	34.0 (40.4)	−69.9 (125.3)
	$Peak_{max}$ (%BW)	105.5 (7.7)	96.9 (15.3)	−9.3 (13.4)
	t_{max} (%CT)	31.6 (16.3)	30.9 (4.4)	6.6 (47.2)
	ROM over gait cycle	104.0 (7.9)	95.3 (15.3)	−9.7 (13.9)

Note: Grey highlight indicates SF% in ± 5% range.

Kinematic symmetry analysis. Figure 5 shows that the SF values and areas of ankle angles were enlarged with increased walking speed, indicating more asymmetry of ankle angle between two limbs with their traditional prostheses while the walking speed increases.

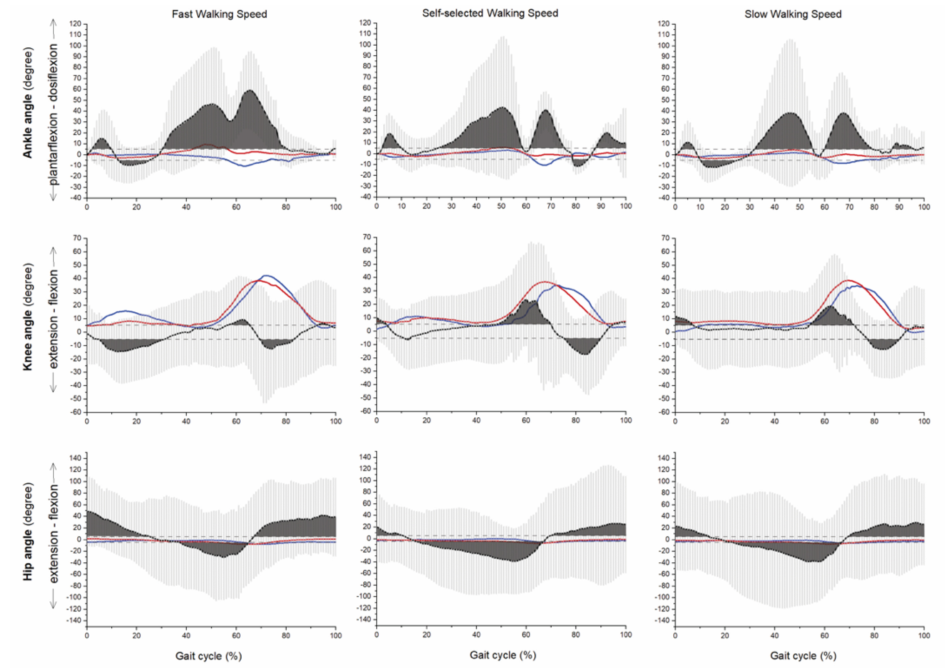

Figure 5: The mean of range of motion and the corresponding SF (%) (solid dark line) in main low extremity joints characterizing hip flexion-extension, knee flexion-extension and ankle dorsi-plantarflexion during different walking speeds. ***Blue and red** solid lines indicate the joint angles of intact limb and residual limb respectively. **Dark** solid line indicates SF (%) of two limb sides. **Light grey** area shows the SD of SF. **Dark grey** area indicates the SF are more than 5%.*

For ankle joint, the values of intact limb were greater during maximum plantarflexion, while the values of residual limb were greater during maximum dorsiflexion with three walking speeds (see **Table 3**). For knee and hip joints, the values of intact limb were greater during maximum extension, while the values of residual limb were greater during maximum flexion with three walking speeds.

Table 3. Mean and ± standard deviation (SD) for the parameters characterizing range of motion (ROM) and the corresponding SF%.

Angle (degree)	Intact	Residual	SF%	
Fast Walking Speed	**Ankle angle**			
	Max plantarflexion	−26.1 (13.5)	−7.6 (2.2)	−19.6 (7.9)
	$t_{\text{max plantarflexion}}$ (%CT)	65.6 (8.0)	23.5 (13.2)	−42.1 (18.3)
	Max dorsiflexion	6.3 (2.9)	49.9 (62.6)	105.7 (44.3)
	$t_{\text{max dorsiflexion}}$ (%CT)	41.3 (19.9)	55.1 (7.1)	13.8 (26.0)
	ROM over gait cycle	32.5 (14.1)	57.4 (61.8)	125.3 (39.0)
	Knee angle			
	Max extension	−8.8 (22.7)	−10.3 (31.3)	−35.0 (30.1)
	$t_{\text{max extension}}$ (%CT)	59.5 (24.0)	60.9 (26.7)	1.4 (32.6)
	Max flexion	50.4 (24.7)	53.6 (35.4)	26.4 (28.9)
	$t_{\text{max flexion}}$ (%CT)	66.3 (17.3)	74.1 (5.4)	7.8 (20.8)
	ROM over gait cycle	59.2 (4.6)	64.0 (13.9)	61.3 (10.2)
	Hip angle			
	Max extension	−10.8 (5.7)	1.2 (31.5)	−41.5 (72.3)
	$t_{\text{max extension}}$ (%CT)	60.3 (15.9)	60.6 (24.5)	−5.9 (16.2)
	Max flexion	2.8 (5.8)	14.3 (31.2)	70.0 (58.0)
	$t_{\text{max flexion}}$ (%CT)	44.2 (19.7)	28.7 (37.1)	−19.9 (29.7)
	ROM over gait cycle	13.6 (5.9)	13.2 (8.3)	111.5 (44.9)
Self-selected Waking Speed	**Ankle angle**			
	Max plantarflexion	−21.0 (6.5)	−10.7 (3.7)	−26.9 (13.6)
	$t_{\text{max plantarflexion}}$ (%CT)	66.9 (9.7)	20.9 (19.3)	−46.1 (27.3)
	Max dorsiflexion	8.4 (7.5)	41.3 (59.9)	88.2 (40.6)
	$t_{\text{max dorsiflexion}}$ (%CT)	43.6 (23.1)	55.4 (14.9)	11.8 (18.5)
	ROM over gait cycle	29.4 (12.2)	51.9 (62.3)	115.1 (33.6)
	Knee angle			
	Max extension	−11.0 (22.1)	−8.6 (30.5)	−37.4 (35.9)
	$t_{\text{max extension}}$ (%CT)	68.4 (22.5)	62.7 (22.9)	−5.7 (27.2)
	Max flexion	45.8 (22.3)	49.8 (28.6)	35.5 (26.2)
	$t_{\text{max flexion}}$ (%CT)	68.4 (17.6)	62.3 (15.8)	−6.1 (4.6)
	ROM over gait cycle	56.8 (6.5)	58.4 (12.3)	72.9 (30.5)
	Hip angle			
	Max extension	−9.7 (4.3)	−10.0 (7.5)	−61.4 (72.5)
	$t_{\text{max extension}}$ (%CT)	59.5 (16.6)	55.7 (16.6)	−3.9 (12.1)
	Max flexion	1.8 (4.6)	1.3 (7.7)	64.4 (71.3)
	$t_{\text{max flexion}}$ (%CT)	42.6 (15.7)	49.5 (33.2)	6.9 (21.4)
	ROM over gait cycle	11.5 (5.0)	11.3 (7.6)	125.7 (35.7)
Slow Waking Speed	**Ankle angle**			
	Max plantarflexion	−20.6 (9.0)	−8.9 (2.8)	−24.1 (13.5)
	$t_{\text{max plantarflexion}}$ (%CT)	65.2 (7.1)	22.3 (23.0)	−42.9 (30.0)
	Max dorsiflexion	8.5 (7.0)	43.3 (61.6)	90.1 (39.2)
	$t_{\text{max dorsiflexion}}$ (%CT)	49.0 (23.1)	53.7 (1.9)	4.7 (24.5)
	ROM over gait cycle	29.1 (12.8)	52.2 (63.3)	114.2 (34.4)
	Knee angle			
	Max extension	−11.1 (22.8)	−7.5 (29.9)	−32.1 (40.7)
	$t_{\text{max extension}}$ (%CT)	66.9 (11.6)	76.3 (19.8)	9.5 (18.0)
	Max flexion	44.4 (22.5)	48.4 (27.2)	34.6 (14.3)
	$t_{\text{max flexion}}$ (%CT)	67.7 (15.4)	69.6 (3.3)	1.9 (12.2)
	ROM over gait cycle	55.5 (10.0)	55.9 (12.9)	66.7 (31.8)
	Hip angle			
	Max extension	−9.7 (3.6)	1.0 (29.4)	−60.8 (65.9)
	$t_{\text{max extension}}$ (%CT)	60.0 (21.6)	61.7 (15.2)	0.3 (22.5)
	Max flexion	2.0 (4.9)	12.7 (29.2)	55.8 (75.3)
	$t_{\text{max flexion}}$ (%CT)	44.1 (20.8)	62.4 (20.2)	14.0 (30.5)
	ROM over gait cycle	11.6 (5.5)	11.6 (5.3)	116.6 (34.6)

Note: Grey highlight indicates SF% in ± 5% range.

CONCLUSION

From the thorough assessment on kinetic and kinematic symmetries, the current prostheses (K2 and K3) can only support the basic daily activities for the unilateral transtibial amputees. The new design of prostheses should therefore focus on kinetic and kinematic parameters such as the symmetry between the residual limb and the intact limb, and energy saving for the amputees during high intensity activities. The results of this study revealed that the current prostheses can only support the basic daily activities for the unilateral transtibial amputees. The study found that the normalized vertical GRF of two limbs increased with increased walking speeds. The corresponding SI was the largest when heel strike with slow walking speed. Gait imbalance was observed during loading response and midstance when the walking speed was increased. The SI values of ankle angles were enlarged with increased walking speed, indicating more asymmetry of ankle angle between two limbs with their traditional prostheses when the walking speed increases. These findings suggest that the current prostheses design may not be sufficient to support the dynamic needs of amputees during high-intensity activities. The prostheses were found to be more effective at slower walking speeds, but as the speed increased, the gait symmetry decreased, indicating a greater difference in function between the prosthetic and intact limb. This could potentially lead to long-term degenerative changes in the joints of the intact limb due to the increased load and asymmetrical gait pattern. Therefore, the study concludes that the design of prostheses should focus on kinetic and kinematic parameters such as the symmetry between the residual limb and the intact limb, and energy saving for the amputees during high-intensity activities. This would involve creating prostheses that can adapt to different walking speeds and provide better support during dynamic activities. This could potentially improve the quality of life for amputees, allowing them to engage in a wider range of activities with greater ease and comfort.

In conclusion, this study provides valuable insights into the limitations of current prostheses designs and highlights the need for more dynamic and adaptable prostheses that can better support the needs of amputees. Future research should focus on developing such prostheses, with a particular emphasis on improving gait symmetry and energy efficiency during high-intensity activities.

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