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Biomechanical mechanisms behind the reduction of knee adduction moment in medial knee thrust gait

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Medial knee osteoarthritis (OA) is the most common OA subtype, and its progression has been strongly linked to increased knee adduction moment (KAM). Among various gait modification strategies, medial knee-thrust gait has emerged to be promising to attenuate KAM. This study aimed to clarify the biomechanical mechanism through which knee-thrust gait reduces KAM. Fourteen healthy young adults were recruited as a first step to understanding the mechanism. KAM was reduced by 21% in the first peak and 36% in the second peak during the knee-thrust gait compared to the normal gait. Stepwise multiple regression indicated that the moment arm (MA) was the primary contributor to both KAM peaks (adj. $R^2 = 0.9$, respectively). Furthermore, the reduction in MA was caused by the lateral deviation of the center of pressure relative to the knee joint center ($C\widehat{O}P$) which outweighed the increase in medial tilting of the ground reaction force observed in knee-thrust gait (adj. $R^2 > 0.80$). These findings suggest that the reduction in KAM peaks is predominantly due to a shortened MA, affected by increased $C\widehat{O}P$ accompanied by wider step width. Understanding this mechanism may offer insights into enhancing gait modification strategies to reduce medial knee loading and potentially slow the progression of medial knee OA. However, since this study was conducted on healthy participants, caution is warranted when generalizing the findings to patients with knee OA.

Keywords Medial knee-thrust gait, Knee adduction moment, Mechanism, Moment arm, Center of pressure

Osteoarthritis (OA) is chronic disease characterized by the degeneration of joint cartilages and bones, which leads to inflammation, pain, and functional impairment[1–3]. Among them, knee OA is the most prevalent form of joint disease[1], with a high prevalence of up to 53% in the elderly population[3–6]. Knee pain is the most common symptom of knee OA[5], and analgesics (NSAIDs) and joint replacement surgery have been commonly suggested to relieve pain and symptoms. However, the effect size of NSAIDs is generally small[7]. The lifespan of joint replacements is limited, lasting approximately 13–14 years[8] and postoperative appropriateness is low, with only 11.8% in men and 17.9% in women, and infections can lead to pain and joint instability[4,7]. Therefore, preventing and delaying the progression of knee OA is important.

Knee OA can affect the medial, lateral, and anterior (patellofemoral) compartments of the knee joint, with medial knee OA being the most common subtype[9]. Since medial knee OA is primarily caused by the load on the compartment[10–15], reducing this load is crucial. Because in-vivo measurement of the load applied to the medial compartment is difficult, the external knee adduction moment (KAM) has been widely accepted as a surrogate marker for the medial load[13,14]. Therefore, reducing KAM is important for preventing and declining of the knee OA[15,16].

Many studies have shown that gait modification strategies, such as medial knee-thrust, trunk-lean, toe-in and out, and wider-step-width, are effective in reducing KAM[17–26]. Among these, knee-thrust, characterized by "rubbing the insides of knees together during walking", showed the highest reduction rate in KAM peaks[27].

The reduction in KAM through knee-thrust was first reported by Fregly et al.[17] for one patient, showing reductions of 50% and 55% for the first and second peaks, respectively. Subsequent studies involving multiple patients reported reductions in the first peak ranging 14–43%[20–23]. Comparable reductions were observed in healthy subjects, with reduction of 44% and 17% for the first and second peaks, respectively, in one healthy adult[18], and reductions ranging 20–41% for the first peak in multiple subjects[19,24].

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However, these studies did not investigate the specific biomechanical mechanism underlying this reduction. In particular, they did not quantify how changes in lower limb posture, ground reaction force (GRF) orientation, or other relevant biomechanical factors contributed to alterations in the KAM. Notably, Fregly et al.[17] and Bokaeian et al.[23] observed a lateral shift of the plantar center of pressure (COP) in the foot reference frame during the knee-thrust gait and suggested its potential contribution to KAM reduction. However, they did not quantitatively link this change to the observed KAM reduction, nor did they assess whether other biomechanical factors, such as lower limb posture or GRF orientation, might play a more dominant role. Addressing these limitations, the present study was designed with a clear focus on quantitatively identifying which gait posture changes and kinetic factors contribute to the reduction in KAM during knee-thrust gait. By integrating gait posture and GRF characteristics, this study aims to provide a clearer and more comprehensive understanding of the mechanisms underlying KAM reduction. In gait modifications, understanding specific mechanisms behind KAM reduction is crucial for enhancing the effectiveness of gait training. Specifically, understanding the relationship between KAM reduction and body posture is anticipated to facilitate better gait modification.

Due to the significant variation in symptoms, deformities, and gait characteristics among patients, identifying a consistent mechanism is likely to be challenging. Abdollahi et al.[28] reported that patients with knee OA exhibit increased postural fluctuations due to pain inhibition, loss of proprioception, and muscle weakness, suggesting that such patient-specific factors can confound gait analysis. In healthy individuals, these confounders are eliminated, allowing the underlying mechanism to be isolated. Moreover, younger healthy adults possess a greater capacity to learn and adapt to novel gait tasks compared to older adults[19], enabling more consistent and faithful implementation of prescribed gait modification. Thus, investigating the mechanism in healthy individuals not only ensures that the findings are free from disease-related factors but also may better capture the genuine effect of gait modification in a faithful implementation of knee-thrust pattern.

Therefore, this research aims to analyze the reduction of KAM and its mechanism by comparing knee-thrust gait with normal gait based on gait posture and kinetics in healthy individuals.

Results

Reduction of KAM

Figure 1 depicts the time trajectories of KAM, GRF magnitude, and moment arm (MA) during the stance phase for the two gait types. Both KAM peaks were significantly lower in the knee-thrust gait compared to the normal gait. Comparable reductions were observed in MA, but the reductions in GRF magnitude (GRFm) were either non-significant or smaller.

The correlation between KAM peaks and MA was exceptionally strong ($r=0.97$ for both peaks), while correlations with GRFm ranged from weak to moderate ($r=0.17$–0.64) and remained weak with gait speed ($r=0.26$–0.27) (Fig. s1). Gait speed exhibited a positive correlation with GRFm only at the second peak ($r=0.60$, Fig. s2).

Table 1 compares KAM peaks and their related factors between two gait types. KAM was reduced by 21% and 36% at the first and second peaks, respectively, through knee-thrust gait. The reduction in MA was 23% and 27% for the first and second peaks, respectively. In contrast, for GRFm, a reduction was observed at the second peak (12%), whereas at the first peak, it showed a slight but non-significant increase (1.6%). Gait speed was also reduced by 38% through knee-thrust gait. ANCOVA confirmed that reductions in both peaks of KAM, MA, and GRFm due to knee-thrust gait remained significant, even after controlling for the effect of gait speed ($p<0.001$) (Table s1). Notably, GRFm at the first peak was increased in ANCOVA.

The results of the stepwise multiple regression analysis for the peaks of KAM are shown in Table 2. MA accounted for 94% of the variance in both peaks of KAM on its own, while the addition of GRFm to the model only marginally increased the explanatory power (R^2) by only 4–5% for both peaks. Gait speed was removed during the stepwise process.

Mechanism of the MA reduction

Figure 2 depicts stick figures comparing the two gait types, and Table 1 presents the major features illustrated in the stick figures. Here, $\widehat{\text{COP}}$ represents the lateral offset of COP relative to KJC. Both COP and knee joint center (KJC) were shifted laterally due to the knee-thrust at the second peak, whereas only COP shifted laterally at the first peak. Notably, the lateral displacement of COP exceeded that of KJC in both peaks, resulting in an increase in $\widehat{\text{COP}}$ by 15(mm/Ht) at the first peak and 10(mm/Ht) at the second peak ($p<0.001$). No significant changes were observed in the mediolateral position of the center of mass (COM). Since the GRF vector originates from the laterally displaced COP and is directed toward the stable COM, the medial tilting of the GRF (θ_{GRF}) increased by 1.5° and 1.3° at the first and second peaks, respectively ($p<0.001$).

Table 1 also presents the step width (SW), and mediolateral COM sway observed throughout the gait cycle. Both SW and COM sway significantly increased due to knee-thrust, and the two variables exhibited a strong positive correlation ($r=0.79$).

Table 2 and Fig. s3 show the effect of $\widehat{\text{COP}}$ and θ_{GRF} on MA. $\widehat{\text{COP}}$ and θ_{GRF} explained 80–86% of the variance in MA at peaks of KAM. Although $\widehat{\text{COP}}$ and θ_{GRF} were strongly positively associated (Fig. s4, Table 2 indicates that $\widehat{\text{COP}}$ negatively impacted MA ($\beta<0$), while θ_{GRF} positively influenced MA ($\beta>0$). Notably, the impact of $\widehat{\text{COP}}$ was 1.6–2.5 times greater than that of θ_{GRF}. $\widehat{\text{COP}}$ was moderately to strongly associated with SW (Fig. s5).

Figure 3 illustrates the plantar COP at the two peaks of KAM within the foot reference frame. While the plantar COP tended to shift medially at both peaks due to knee-thrust, this change did not reach statistical significance ($p>0.05$).

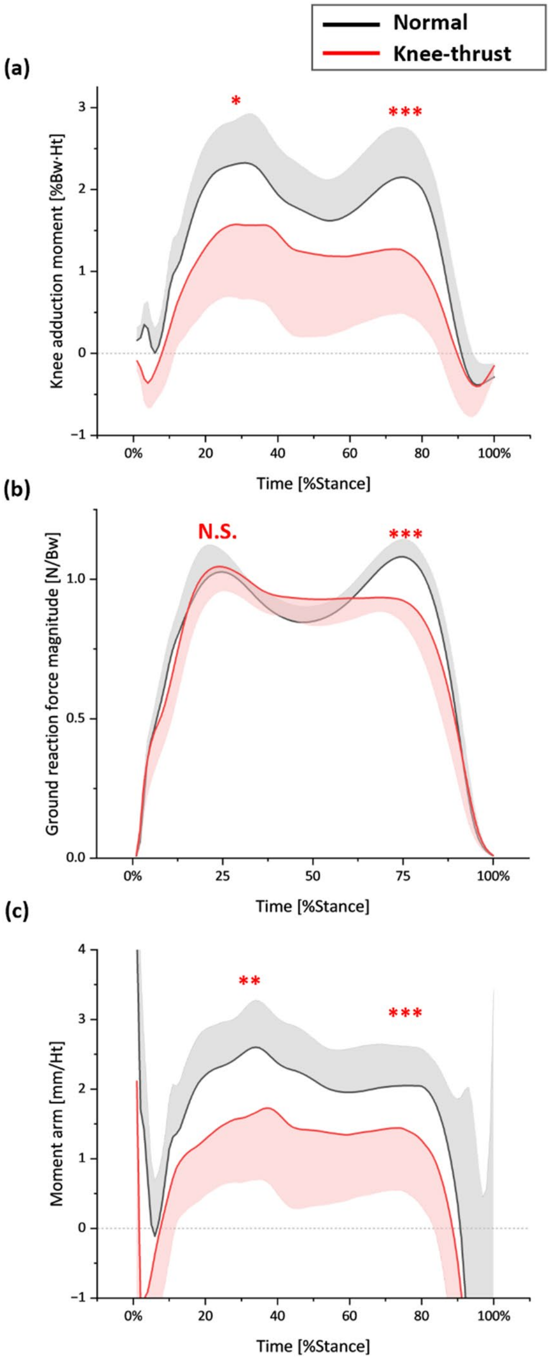

Fig. 1. Comparison between gait strategies in knee adduction moment (KAM) (**a**), ground reaction force magnitude (**b**), and moment arm (**c**). The abbreviations used for normalization of the vertical axis variables indicate Bw: Body weight, Ht: Height. *$p < 0.05$, ***$p < 0.001$, N.S.: non-significant.

Discussion

The key findings of the present study are: (1) Both peaks of KAM were reduced through knee-thrust even after accounting for the influence of gait speed, (2) The primary factor contributing to the reduction in KAM was MA, (3) The primary cause of the reduction in MA was the lateral deviation of COP relative to KJC.

Among the key findings, the most important is the pronounced lateral deviation of $\widehat{COP}$ during knee-thrust gait. This discovery matters because it isolates a gait-modifiable geometric target, that is to increase $\widehat{COP}$ which shortens MA and thereby reduces KAM. Moreover, this discovery is particularly significant because previous studies merely speculated about the associations between postural changes and KAM and were unable to empirically verify them. Accordingly, the remainder of the Discussion explains the decrease in KAM by starting from changes in $\widehat{COP}$.

Outcome	Factor	Normal	Knee-thrust	Difference	Effect size	Reduction [%]	Change
First peak	KAM [%Bw·Ht]	2.51 ± 0.53	1.98 ± 0.78	0.53 ± 0.25*	0.78	21.2% ± 10.1	Decrease
	GRFm [N/Bw]	0.99 ± 0.06	1.01 ± 0.07	-0.02 ± 0.02 N.S.	−0.21	−1.6% ± 1.9	–
	MA [mm/Ht]	2.71 ± 0.57	2.08 ± 0.80	0.62 ± 0.23**	0.87	23.0% ± 8.3	Decrease
	COPx [mm/Ht]	29.2 ± 9.0	13.9 ± 19.1	15.4 ± 10.1**	0.93	–	Lateral shift
	KJCx [mm/Ht]	16.5 ± 8.2	16.3 ± 14.1	0.2 ± 5.9 N.S.	0.02	–	–
	$\widehat{COP}$ [mm/Ht]	-12.7 ± 10.0	2.5 ± 17.6	15.2 ± 7.5***	−1.62	–	Lateral deviation
	COMx [mm/Ht]	57.1 ± 5.6	55.0 ± 8.6	2.1 ± 3.0 N.S.	0.36	–	–
	θ_{GRF} [°]	3.3 ± 0.8	4.7 ± 1.5	1.5 ± 0.8**	−0.98	–	Medial tilting
Second peaks	KAM [%Bw·Ht]	2.20 ± 0.60	1.42 ± 0.77	0.78 ± 0.18***	1.74	35.6% ± 8.0	Decrease
	GRFm [N/Bw]	1.07 ± 0.08	0.94 ± 0.08	0.13 ± 0.01***	1.89	12.0% ± 0.5	Decrease
	MA [mm/Ht]	2.13 ± 0.54	1.56 ± 0.87	0.57 ± 0.33***	1.12	26.7% ± 15.5	Decrease
	COPx [mm/Ht]	22.9 ± 13.5	5.6 ± 17.6	17.3 ± 4.2**	0.92	–	Lateral shift
	KJCx [mm/Ht]	15.4 ± 10.4	8.7 ± 12.1	6.7 ± 1.7*	0.61	–	Lateral shift
	$\widehat{COP}$ [mm/Ht]	-7.5 ± 13.3	3.0 ± 17.3	10.5 ± 4.0***	−1.13	–	Lateral deviation
	COMx [mm/Ht]	52.9 ± 9.5	51.7 ± 9.6	1.2 ± 0.1 N.S.	0.19	–	–
	θ_{GRF} [°]	2.7 ± 1.0	3.9 ± 1.1	1.3 ± 0.1**	−0.81	–	Medial tilting
Gait cycle	Speed [km/h*Ht]	2.40 ± 0.25	1.47 ± 0.42	0.93 ± 0.17***	2.57	38.8% ± 7.2	Decrease
	SW [mm/Ht]	61.7 ± 16.3	124.0 ± 32.5	62.4 ± 16.2***	−2.28	–	Increase
	COM sway [mm/Ht]	24.1 ± 7.2	71.7 ± 22.2	47.6 ± 15.0***	−2.20	–	Increase

Table 1. Key features. Column "Change" indicates the change in a variable due to the knee-thrust compared to that of normal gait. Subscript x: mediolateral coordinate in the global reference frame where smaller values indicate greater displacement. GRFm: ground reaction force magnitude, MA: moment arm, COP: center of pressure, KJC: knee joint center, $\widehat{COP}$x: lateral displacement of COPx with reference to KJCx, i.e., $\widehat{COP}$x= - (COPx - KJCx), COM: center of mass, θ_{GRF}: medial tilting angle of the GRF, SW: step width, COM sway: mediolateral sway of COM (The correlation between SW and COM sway was $r = 0.79$ ($p < 0.001$)). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, N.S.: non-significant.

Outcome		Factor	β	Adj. R^2	ΔAdj. R^2
KAM	First peak	MA [mm/Ht]	0.98***	0.99***	0.94
		GRFm [N/Bw]	0.22***		0.05
	Second peak	MA [mm/Ht]	0.86***	0.98***	0.94
		GRFm [N/Bw]	0.22***		0.04
MA	First peak	$\widehat{COP}$ [mm/Ht]	-1.31***	0.80***	0.51
		θ_{GRF} [°]	0.80***		0.29
	Second peak	$\widehat{COP}$ [mm/Ht]	−1.25***	0.86***	0.76
		θ_{GRF} [°]	0.50***		0.10

Table 2. Stepwise multiple regression analysis for the peaks of KAM. MA: moment arm; ***$p < 0.001$.

The increase in $\widehat{COP}$ appears to result from the combined effect of two phenomena. First, the increased SW in knee-thrust gait, which is consistent with Booij et al.[22], causes the foot and COP to shift laterally, as evidenced by the significant association between $\widehat{COP}$ and SW (Fig. s5). Second, the instruction to walk with the knees brushing each other causes the KJC to shift inward relative to the foot. It is worth noting that the increase in SW seems to be an unconscious strategy chosen by the participants in order to push the knees inward. In the studies of gait modification with reduced KAM peaks, increases in SW were commonly reported with toe-in gait[22,24–26], trunk-lean gait[24,26], and knee-thrust gait[22]. This suggests that the lateral shift of the COP resulting from an increase in SW, along with the accompanying reduction in the MA, might be a common key factor in the reduction of KAM in gait modification strategies.

In some previous studies, Fregly et al.[17] and Bokaeian et al.[23] reported that, during knee-thrust gait, the COP shifts laterally on the plantar surface. They also argued that this lateral shift of the COP contributes to a reduction in KAM through a decrease in MA; however, they did not provide any evidence to support this claim. In contrast, this study found that the COP within the foot shifted medially, though not significantly (Fig. 3). Instead, the lateral shift of the COP in the knee reference frame was overwhelmingly larger than the medial shift in the plantar surface and was shown to be associated with a reduction in MA (Table 2). This indicates that changes in the overall lower-limb posture, rather than shifts of the COP within the foot, have a greater impact on

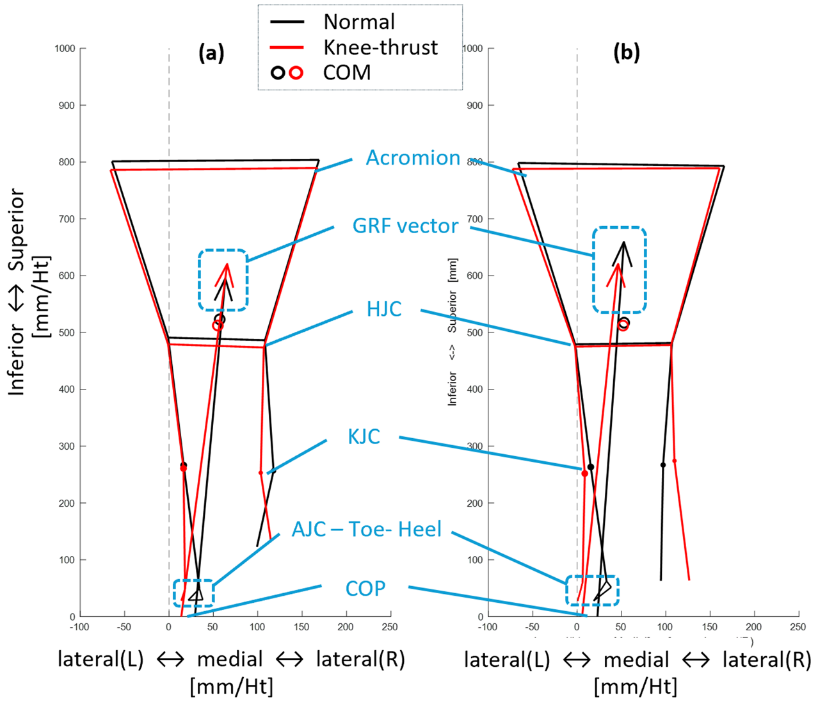

Fig. 2. Stick figures displayed in the global coronal plane (rear view) at the first peak (**a**) and second peak (**b**) of the knee adduction moment. The data shown in the figures represent the average value.

the reduction in MA. The lateral shift of the COP on the plantar surface observed by Fregly et al.[17] and Bokaeian et al.[23] may have been a strategy adopted due to the instruction to perform knee-thrust without altering foot positioning[17]. Restricting foot placement can constrain lower-limb kinematics, potentially amplifying the lateral shift of the COP within the plantar surface, generating sufficient medial force to thrust the knees inward. In contrast, the present study allowed free foot placement, which resulted in the change in overall lower-limb posture and produced a lateral shift of the COP in the knee reference frame. The insignificant medial shift of the plantar COP may be associated with foot contact in a more valgus knee posture. In other words, when there are no constraints on foot positioning, an unconscious strategy of a lateral shift of the COP by increased SW may have been adopted to facilitate knee-thrust. This could represent a more practical and easier-to-perform strategy for patients.

The increased $\widehat{COP}$ caused the GRF vector to tilt medially (Fig. 2; Table 1). These two factors— $\widehat{COP}$ and GRF angle—were shown to accurately predict MA (Table 2). Notably, the increase in $\widehat{COP}$ overwhelmed the opposite effect of the medial tilting of the GRF vector, ultimately achieving a reduction in MA. Therefore, the primary cause of the reduction in MA is concluded to be the increase in $\widehat{COP}$. The medial tilting of the GRF vector during knee-thrust gait can be interpreted as follows. While the COP, which serves as the origin of the GRF vector, shifts laterally due to the increased SW, the position of the COM remains largely unchanged (Fig. 2; Table 1). As a result, the GRF vector, directed from the COP toward the vicinity of the COM, inevitably tilts more medially. This medial tilting of the GRF vector, under normal circumstances, would increase the MA of GRF vector from the KJC. However, since the lateral shift of KJC is less than that of COP (i.e. increase in $\widehat{COP}$), the GRF vector comes closer to the KJC. That is, increase in $\widehat{COP}$ overwhelms the effect of the medial tilting of the GRF vector.

One prior study speculated that the kinematic modifications in knee and hip joints in knee-thrust gait are associated with reduced KAM, but failed to provide evidence[19]. In contrast, we found that increased $\widehat{COP}$ resulting from postural change was a major factor for shortening MA with concrete evidence.

The primary factor contributing to the reduction in KAM was MA rather than GRFm (Table 2). These findings align with Baniasad et al.[29], who asserted that an increased MA is associated with an increase in KAM in patients, and with Schache et al.[18], who suggested that knee-thrust gait (in a single healthy normal subject) reduced KAM by decreasing MA rather than GRFm, despite their inability to establish concrete relationships. The reduction in GRFm during the second peak may indicate a decrease in the force responsible for generating acceleration of the COM during the push-off phase, resulting in less dynamic motion. This is thought to contribute to the decrease in gait speed (Table 1 and Fig. s2).

In this study, bilateral knee-thrust gait performed by healthy adults reduced the first and second peaks of KAM by 21% and 36%, respectively. Notably, the reduction was greater in the second peak than the first peak, suggesting a larger effect during the late stance phase. This pattern is consistent with the findings of Fregly et al.[17] but contrasts with those of Gerbrands et al.[20] and Lindsey et al.[24], who observed larger reductions in the first peak. One likely reason is the differences in gait instructions among studies. In the latter studies[20,24], participants were instructed to thrust only one knee during the stance phase (unilateral knee-thrust). In contrast, our

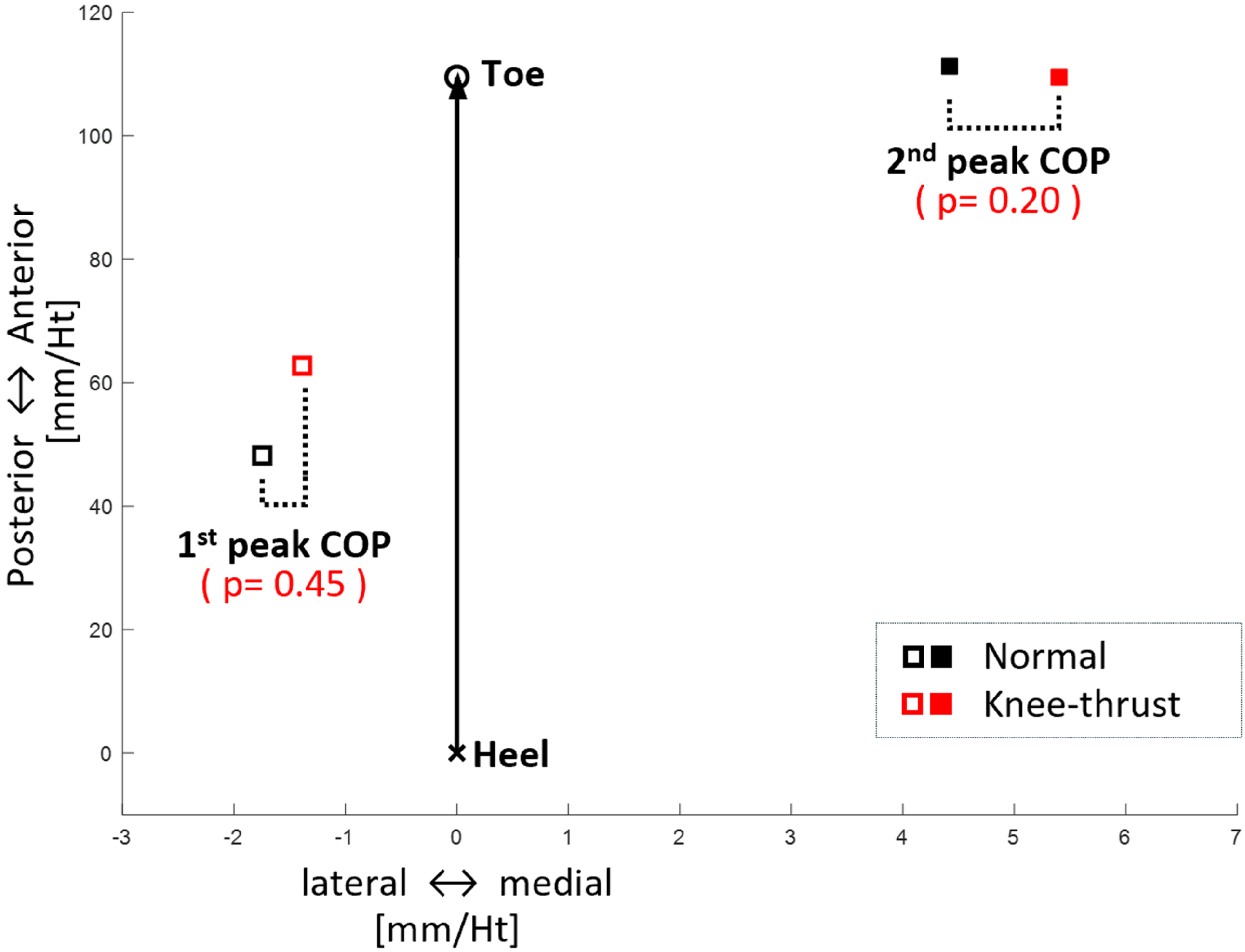

Fig. 3. Plantar COP at the peaks of KAM in two gait types.

study and Fregly et al.[17] allowed participants to thrust both knees inward (bilateral knee-thrust). This bilateral approach may have promoted a more symmetrical change in lower-limb kinematics and contributed to the larger reduction in the second peak. Furthermore, our results show that the $\widehat{COP}$ at the second peak during knee-thrust gait tended to be greater than that at the first peak (Table 1). This suggests that in the case of bilateral thrust, knee-thrusting is relatively more pronounced or persists during the late stance compared to the early stance. Conversely, in the case of unilateral thrust, knee-thrusting may be more prominent from the early stance, potentially leading to a greater reduction in first peak KAM. To improve patient compliance with gait modification, ease, comfort, and not appearing awkward are critical factors[24,30]. From this perspective, bilateral thrust appears to be advantageous.

This study is the first to quantitatively demonstrate, in healthy adults performing bilateral knee-thrust gait, that this reduction is associated with a decrease in MA driven by the lateral shift of COP relative to the knee. These findings offer foundational information for effective gait modification strategies and are expected to aid in patient training and evaluation aimed at slowing the progression of OA. Importantly, elucidating this mechanism may not only enhance the targeted application of knee-thrust gait but also provide a framework for optimizing other gait modification strategies, as it identifies the key biomechanical target —increasing $\widehat{COP}$ to reduce MA. Such insights have the potential to guide the development of personalized rehabilitation programs and ultimately slow the progression of medial knee OA, thereby enhancing patients' overall quality of life.

One important limitation should, however, be considered when interpreting or generalizing the findings, as the mechanism identified in this study was derived from a specific condition: healthy adults and bilateral knee-thrust gait. Structural changes (e.g., varus alignment and joint space narrowing), pain, impaired muscle function and motor control, and diminished adaptability may limit patient compliance and affect the feasibility and effectiveness of implementing knee-thrust gait. Therefore, the proposed mechanism needs to be validated in patient populations. Limitations include that the analysis was performed only for KAM in the frontal plane. Further research is needed to investigate the effect of knee-thrust gait on the knee flexion moment, which has been shown to increase the overall knee contact force[31]. Furthermore, biomechanical interactions across the entire body (including the hip, knee, ankle, and upper body) should be examined to gain a deeper understanding of the mechanisms underlying KAM reduction.

Methods
Experiments
Both too large and too small sample sizes are undesirable[32]. Accordingly, an a priori power analysis ($\alpha = 0.05$, power = 0.95) was conducted using an expected effect size derived from a 20% difference in KAM (with a 15% SD from[19] between two gait types. The analysis indicated a minimum sample size of 10, and thus fourteen participants were recruited to ensure sufficient statistical power. Fourteen healthy adults (7 male and 7 female) participated in this experiment (Table s2), including only those who were able to walk independently without assistive devices, and excluding those with musculoskeletal or neurological diseases or a history of lower limb surgery within the past three months or any current pain or discomfort affecting gait. The experiment was conducted after explaining the research details to the participants and obtaining their informed consent, and the experimental procedures were approved by the institutional review board prior to implementation (IRB #: 7001355-202011-HR40). All methods were performed in accordance with the relevant guidelines and regulations.

The experiment was conducted in a motion laboratory, equipped with nine motion capture cameras (Eagle, Motion Analysis Corp, USA) and two force plates (AMTI, CA). Helen-Hayes full-body marker set (Fig. s6) was used for the motion capture. Participants were instructed to walk along a 6.5 m path while wearing an exclusive motion capture suit (MS-FS, CS, and WB, 3 × 3 Designs, Canada) (Fig. s7). Participants performed 10 trials for each of normal gait and knee-thrust gait conditions, with a 30-minute rest period between trials. In this study, knee-thrust gait refers to a walking strategy in which participants walk "rubbing the insides of the knees together", referred to here as bilateral knee-thrust condition (Fig. s8). For the knee-thrust condition, participants were instructed to move both knees medially during walking as if rubbing the insides of the knees together, while maintaining a comfortable posture. To familiarize themselves with the task, participants practiced 10 to 20 min before the experiment.

Analysis
Seven trial data with the least marker loss were selected from the 10 trials for each participant, and the stance phase of the left foot was used for analysis. Joint coordinates data were obtained from kinematic data captured at 120 Hz using Cortex software (Motion Analysis Corp., CA). All marker trajectories were filtered using a 4th-order low-pass Butterworth filter, with the filter order fixed as recommended by Cortex and Wang et al.[33], and a cutoff frequency of 6 Hz applied to eliminate high-frequency noise during gait[33,34].

a. Analyses in the local coronal plane of the knee.

Since KAM is a value in the knee's coronal plane (tibia reference frame), the related MA and the magnitude of the GRF vector were also calculated in this plane. KAM was extracted using the inverse dynamics provided by Cortex. While the other variables were obtained using a custom-made program in MATLAB (See Supplementary Information for details). Specifically, the MA was calculated using the KJC, GRF, and COP (Eq. s1-s4 and Fig. s9). MA is defined as the perpendicular distance from the KJC to the GRF vector on the coronal plane. It was derived through two steps: (1) converting the coordinates of COP and GRF vector into the knee's local axes, and (2) calculating the distance from the KJC to GRF vector line projected on to the coronal plane of the knee. The first step involved translating the origin of coordinates from the global coordinate system to the KJC and rotating the axes to align with the knee's local axes (Eq. s1-s3). This resulted in the COP and GRF vector being represented in the knee's local coordinates. In the second step, the GRF vector and COP were projected onto the knee's coronal plane (Fig. s9). The moment arm r was calculated using the determinant of the vectors, as described in (Eq. s4). Additionally, the GRF magnitude was determined by taking the absolute value of the GRF vector projected onto the coronal plane. To reduce the effect of physical difference among participants, KAM was normalized to the product of body weight (Bw) and body height (Ht), while MA was normalized to Ht, and GRFm to Bw.

b. Analyses in the global coordinate system.

To investigate the mechanism of KAM reduction based on whole-body posture and kinetics, all kinematic and kinetic data were analyzed in the global coordinate system, as presenting the data in a unified framework enhances intuitive understanding.

As a preprocessing step, slight misalignment between the participant's progression line and the anteroposterior direction of the global coordinate system was corrected by rotating all data (marker and GRF vector coordinates) within the transverse plane. Specifically, all data coordinates were rotated so that the progression line (connecting the ankle joint centers at the initial and terminal points of a single gait cycle) was aligned with the anteroposterior axis of the global coordinate system using custom-made MATLAB program by Euler rotation (Eq. s3). All subsequent analyses were performed using the corrected data.

To analyze the mechanism of KAM reduction, stick figures were constructed in the global coronal plane, incorporating anatomical landmarks, the GRF vector, and the COP. At this stage, the mediolateral coordinate of the hip joint center (HJC) of the left leg was set to zero to enable comparisons between the two gait types. As anatomical landmarks, the acromion, HJC, KJC, AJC, COM, toe marker, and heel marker were used. The COP and the GRF vector, originating from the COP, were visualized. All coordinate data used in the stick figures were normalized to height. Additionally, the medial tilting angle of the GRF vector and the $\widehat{\mathrm{COP}}$ (representing the lateral deviation of the COP relative to the KJC) were calculated. The average of all trials across all subjects was used to generate stick figures for each gait type.

As gait cycle features, gait speed was calculated by dividing the COM displacement during the gait cycle by the cycle time, while COM sway was defined as the range of the mediolateral coordinate of COM during the gait cycle, normalized to height.

We also investigated the mediolateral deviation of the plantar COP at the two peaks of KAM. The local plantar axes of the foot were used to compare the two gait types. Specifically, the heel served as the origin, and the heel-toe line was designated as the vertical axis. Heel and toe marker positions were extracted at the mid-point of the mid-stance phase.

c. Statistical Analysis.

Paired t-test was conducted to assess differences in KAM, GRFm, MA, and gait speed between the two gait types. In addition to statistical significance, the effect sizes (Cohen's d) were calculated to assess the magnitude of the differences. For the pairwise comparison, a single data value (the average of seven gait trials) was used per subject for each gait type. Furthermore, to exclude the potential effect of gait speed on KAM-related variables, ANCOVA was applied with gait speed included as a covariate.

KAM can be approximated as the product of GRFm and MA[35,36]; therefore, stepwise multiple regression was employed to evaluate the influence of GRFm and MA on KAM. The entry and removal criteria of independent variables in the stepwise process were set at p-values of 0.001 and 0.01, respectively, based on F-statistics.

SW and COM sway, as gait cycle features, were compared between the two gait strategies using a paired t-test, and the effect sizes were also calculated. Their relationship was subsequently assessed using correlation analysis.

To identify the cause of the reduction in MA within the stick figure representation, a stepwise multiple regression analysis was conducted with $\widehat{COP}$ and GRF tilt angle as independent factors.

All statistical analyses of the processed data were carried out using SPSS 26 for Windows (IBM Corp., Armonk, NY). Multiple-comparison corrections, such as the Bonferroni procedure, were not applied in order to preserve statistical power, as these corrections can substantially increase type II error and reduce power[37–41]. Given the study's emphasis on effect size interpretation and consistency across analyses, we prioritized maintaining statistical power over applying excessively conservative adjustments.

Data Availability

All data generated and/or analyzed during this study are included in this published article.

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Author contributions

G.M. Eom, J.H. Kim, and H.S. Shin contributed to the conceptualization of the study and developed the methodology. J.H. Kim, H.S. Shin, S.M. Lee, N.Y. Kim, J.H. Jung, and H. Ryu conducted the experiments. J.H. Kim analyzed the data, drafted the manuscript, and prepared the visualizations. G.M. Eom supervised the whole project.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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