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Original Article

Effects of body mass and sex on kinematics and kinetics of the lower extremity during stair ascent and descent in older adults

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ABSTRACT

The effects of body mass and sex on lower limb biomechanics during ascent and descent were examined in participants aged 50 to 75 with normal weight ($n = 19$), overweight ($n = 18$), and obese ($n = 8$). Peak joint angles and joint moment of the lower limb were analyzed with the VICON motion analysis system. Results from multivariate analysis of variance showed that during descent, the overweight participants had significantly higher knee extensor moment (0.98 ± 0.30 N•m/kg^{-1}) than the normal-weight participants (0.70 ± 0.29 N•m/kg^{-1}). The obese group had significantly higher ankle abductor moment (0.21 ± 0.11 N•m/kg^{-1}) than the normal weight (0.12 ± 0.08 N•m/kg^{-1}) and overweight groups (0.09 ± 0.06 N•m/kg^{-1}). During ascent, the obese participants had significant higher hip flexor moment (0.42 ± 0.20 N•m/kg^{-1}) than overweight participants (0.22 ± 0.17 N•m/kg^{-1}). Significant sex differences were found in knee extension angles (4.2 ± 3.4° vs 7.0 ± 3.3°) during descent, plantar flexion angles during ascent (23.7 ± 5.3° vs 15.6 ± 3.7°) and descent (29.9 ± 5.0° vs 22.1 ± 7.9°), and ankle adduction angles (6.8 ± 4.8° vs 2.5 ± 2.5°) during ascent. It is concluded that body mass has significant impact on joint loading of lower limbs during stair walking. Being overweight and obese increased hip joint loading during ascent, and knee and ankle joint loading during descent in older adults. Sex difference in joint kinematics was presented during stair walking regardless of the body mass.

Introduction

Stair climbing is a common daily locomotion and is challenging for some individuals as it has high demands on the musculoskeletal and cardiovascular systems. In the past two decades, biomechanics studies on stair walking that utilized simulated staircase set-ups in gait laboratories have been performed in adults with normal body weights. During ascent, the knee and hip joints extend forward in the early stance phase to overcome the force of gravity.[1] Therefore, more joint moments are required during stair ascent than during walking and the joints experience higher loadings in the former activity.[2] In contrast to ascent, flexion occurs at the hip and knee during descent to control the force of gravity.[3,4]

Stair climbing may be more challenging for people with larger body masses, such as obese and overweight individuals, because the forces on the lower extremities can be higher compared with leveled walking.[5,6] The understanding on the lower extremity biomechanics in people with larger body mass, such as obese or overweight, is severely limited. To the author's knowledge, only a few studies on the kinetic aspects of stair climbing in obese individuals have been published. Mazlan and co-workers[7] studied biomechanics of the lower limb in young obese individuals (23.65 ± 2.26 Years) during ascent. They found that obese individuals adopted an altered movement pattern with higher hip joint moments during ascent than normal-weight individuals along the three movement planes. Strutzenberger et al.[8] studied joint biomechanics of the lower limb in obese and normal-weight children during stair climbing and found that obese children had a significantly larger knee extensor moment during descent. The above study findings are from young people and children, whether obesity or overweight causes changes in the lower extremity biomechanics in older people is unclear. Moreover, it is unknow whether there is sex difference in kinematics and kinetics of lower limb during stair walking as fat tissue distribution pattern are different between older man and women that might influence biomechanics of lower limb.

Research data indicate that the altered joint biomechanics, such as increased joint loading acting on weight-bearing joints, significantly contribute to osteoarthritis (OA) onset and progression.[9,10] Lohmander et al. found that all obesity measures, including body mass, body mass index (BMI), and waist circumference, were associated with the development of knee and hip OA.[11] Evidently, our knowledge on the lower

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extremity mechanics of obese or overweight people during challenged locomotion, such as stair climbing, is lacking.[12–14] Moreover, whether sex differences in lower limb biomechanics during stair ascent and descent in the population is unknow. Therefore, it is needed to understand whether older obese or overweight adults change their lower extremity biomechanics during stair climbing compared with normal-weight people and whether there is sex difference in the lower limb biomechanics during stair climbing. The purpose of this study was to examine the effects of body mass and sex on the kinematics and kinetics of the lower limb of normal-weight, overweight, and obese participants during stair ascent and descent. The findings from this study could add understanding to the joint biomechanics of obese and overweight people during stair climbing.

Materials and method

Participants

Participants were recruited through distributing information letter and posters in local community centers, university campus, and local clinics. An introductory presentation about the study was given to the people who were involved in programs of local community centers, such as reading, cooking, dancing and exercise. The following participants were recruited for the study: 20 normal-weight individuals, with 9 males and 11 females (61.2 ± 6.0 years; 163.8 ± 7.7 cm; 59.5 ± 7.9 kg); 21 overweight individuals, with 14 males and 7 females, (59.4 ± 6.0 years; 170.4 cm ± 9.8; 78.9 ± 11.4 kg); and 11 obese individuals, with 3 males and 8 females (58.1 ± 6.0 years; 166.7 ± 8.6 cm; 93.8 ± 12.8 kg). Table 1 presents the demographical data of the participants. The participants were classified into three groups, the normal weight, overweight, and obese group, based on their BMIs. Those with BMI of 18.5–24.9 kg m^{-2} were classified as normal weight, whereas individuals with BMI of 25.0–29.9 kg m^{-2} were classified as overweight. Moreover, those with BMI of 30.0–34.9 kg m^{-2} were classified as obese class I.[15] The participants were eligible to participate in the present study if they were between the ages of 50 years to 75 years and have BMI of 18.5–34.9 kg m^{-2}. Prior to the experiment, the participants were asked to complete a questionnaire of their medical history to ensure that they did not experience any neuromuscular disorders, musculoskeletal injuries, cardiorespiratory diseases, and weight fluctuations in the past 6 months. This study was approved by the University of Ottawa research ethics committee, and all participants were required to sign an informed consent form.

Data collection

The experimental staircase illustrated in Figure 1 comprised of three steps at 17.8 cm high and 28 cm deep, with the first and second steps built with portable force plates (Model 9286AA, Kistler Instruments Corp, Winterhur, and Swtz). Four force plates, two portable Kistler built into the staircase, and two Bertec (Model FP 4060-08, Bertec Corporation, Columbus, OH, USA) built on the ground were used to record the ground reaction force at 1000 Hz. A motion capturing system with ten infrared cameras (Vicon MX-13, Oxford Metrics, Oxford, UK) was used to record the participant's 3D movement at 200 Hz as they ascended and descended the staircase without using the handrails. Prior to data collection, each participant was asked to change into a body suit or tightly fit clothing to reduce movement of the reflective markers. The participant's anthropometric data were collected. Forty-three reflective markers were placed on each participant's anatomical landmarks outlined by University of Ottawa Motion Analysis Model (UOMAM) that was developed based on Plug-in-Gait marker set (Oxford Metrics, Oxford, UK) and the Helen Hayes marker set.[16] The participants were allowed to practice ascending and descending the staircase at their own pace. When ready, each participant was asked to ascend the staircase with the right foot striking the initial force plate on the first step and then on the third step. During descent, the participants were asked to start with the right foot striking the force plate on the second step and then on the force plate located on the ground. Each of the participants was asked to ascend and descend the stairs at a comfortable speed for five trials with their right legs as lead leg.

Table 1
Participants' information (Means and standard deviations).

Group	Participants	Age (years)	BM[a] (kg)	BH (cm)	BMI[a] (kg·m^{-2})
Normal	n = 19 (M: 8; F:11)	61.4 ± 6.1	59.5 ± 7.8	163.8 ± 7.9	22.1 ± 1.8
Overweight	n = 18 (M:14; F:4)	59.7 ± 6.2	81.3 ± 10.2	172.1 ± 9.3	27.4 ± 1.3
Obese	n = 8 (M:3; F:5)	60.3 ± 5.6	93.3 ± 9.9	167.6 ± 10.0	33.3 ± 2.5

M, male; F, female; BM, body mass; BH, body height; BMI, body mass index.
[a] , $p < 0.05$, indicates a significant difference between the three groups.

Data processing and analysis

All motion capture data were filtered using a generalized cross-validated spline technique. VICON Nexus (v1.7.1) and the UOMAM model were used to calculate the hip, knee, and ankle angles for the frontal and sagittal planes. Once the joint angles were computed, the data were exported from Nexus to Excel (Microsoft, Washington, USA), in which the maximum angle, minimum angle, and range of motion (ROM) at each joint were determined. All trials were cropped and then normalized based on a 100% gait cycle. The stair climbing data from each participant were analyzed based on two consecutive strides for the right leg. The stride period was normalized to the gait cycle (%) for stair climbing. The period in which the heel strike and toe-off occurred was visually inspected by examining the position of the virtual marker on the heel and toe of each participant as he/she contacted and left the ground, respectively.

The data of the ground reaction forces were filtered using a fourth-order 7 Hz Butterworth filter to eliminate the slight oscillation of the staircase. The hip, knee, and ankle moments were calculated based on the inverse dynamics model. The moment of force at each joint were calculated based on the participant's anthropometric measurements and UOMAM model. Joint moment of force data was exported from Nexus to Excel (Microsoft, Washington, USA), where they were normalized by each participant's body mass to allow comparison between participants.

All data were expressed as mean ± standard deviation. The mean was calculated by taking the average of the five trials of each participant's stair climbing. A grand average was used to calculate the average of the kinematics and kinetics data. The peaks for the measures were separately extracted for each trial and then averaged. A students' version Statistical Package for Social Science (SPSS) version 20.0 software for Windows (SPSS Science, Chicago, Illinois) was used for statistical analysis. The independent variables in the study were "sex" (two levels: male and female) and "mass" (three levels: normal weight, overweight, and obese). The two-way MANOVA analysis was also used to determine whether a significant interaction was present between "sex" and "body mass" on the dependent variables. The dependent variables were the peak joint angles, ROM, and joint moment of force. As no significant interaction and major effect of gender in kinetic measures were found, the data from the males and females were pooled. A one-way analysis of variance (ANOVA) analysis and Tukey's Post-hoc test was then performed to further investigate whether the masses have any significant difference. The significance level was set at $p < 0.05$ for all statistical tests.

Fig. 1. Staircase setting and motion data collection.

Results

Kinematics

No significant interaction was found between mass and sex in the peak joint angles (F (48) = 1.072, p = 0.387) and ROM (F (24) = 0.716, p = 0.815) during ascent and descent. The participants' sex had a significant effect on the peak joint angles (F (24) = 4.393, p = 0.002) and ROM (F (12) = 4.386, p = 0.001) at the knee and ankle, whereas the participants' body mass did not influence these variables. Table 2 presents means and standard deviations of the peak joint angles and ROM in the sagittal and frontal plane during stair climbing for females and males.

For ascent, a significant difference was found in ROM of ankle dorsiflexion/plantarflexion. Females presented significantly bigger ROM of ankle (p = 0.007) and peak plantar flexion angles ($p < 0.001$) than males. And females showed significantly bigger ROM of hip abduction/adduction (p = 0.006) and ROM of ankle abduction/adduction (p = 0.007) than males. For the descent, significant differences were found in the ROM of knee and ankle in sagittal motion. Female participants had a significantly smaller peak knee extension angle (p = 0.012) compared with the males. The females' overall ROM at the knee was significantly larger ($p < 0.001$) than that of the males. At the ankle, the female participants plantarflexed their ankles more than the males during descent (p = 0.004). The females' sagittal ROM at the ankle was significantly larger than that of the males during descent (p = 0.003). And during descent, the females showed significantly smaller knee abduction angle (p = 0.002) than the males.

Kinetics

The MANOVA results revealed no significant interaction between sex and mass (F (34) = 0.594, p = 0.943). Body mass had a significant

Table 2
Means and standard deviations for peak joint angles and range of motion (°) in the sagittal and frontal plane during stair climbing for females ($n = 20$) and males ($n = 25$).

Ascent		Female	Male	*p*-value
Hip	Flexion	70.2 ± 7.3	67.4 ± 4.7	0.066
	Extension	8.8 ± 6.1	7.9 ± 6.2	0.385
	ROM	62.8 ± 4.2	60.0 ± 4.8	0.092
Knee	Flexion	99.1 ± 6.3	95.7 ± 5.1	0.138
	Extension	7.3 ± 5.4	7.6 ± 6.5	0.753
	ROM	92.3 ± 8.6	88.2 ± 5.6	0.088
Ankle	DF	11.3 ± 4.1	14.5 ± 5.6	0.366
	PF[a]	23.7 ± 5.3	15.6 ± 3.7	< 0.001
	ROM[a]	35.9 ± 5.2	31.2 ± 5.7	0.007
Hip	Adduction	7.8 ± 4.6	4.6 ± 4.6	0.076
	Abduction	9.1 ± 3.4	8.4 ± 3.6	0.702
	ROM[a]	17.3 ± 3.2	13.2 ± 4.5	0.006
Knee	Abduction	2.7 ± 4.7	2.3 ± 4.3	0.150
	Adduction	8.6 ± 17.0	15.7 ± 15.3	0.064
	ROM	17.3 ± 9.4	19.1 ± 10.9	0.564
Ankle	Adduction[a]	6.8 ± 4.8	2.5 ± 2.5	0.001
	Abduction	1.9 ± 1.0	1.6 ± 1.7	0.329
	ROM[a]	9.5 ± 4.3	6.8 ± 2.7	0.017
Descent		**Female**	**Male**	***p*-value**
Hip	Flexion	42.7 ± 9.2	41.3 ± 5.6	0.495
	Extension	12.2 ± 7.5	12.3 ± 5.5	0.528
	ROM	30.5 ± 4.3	29.1 ± 3.6	0.847
Knee	Flexion	97.6 ± 5.6	95.4 ± 4.6	0.091
	Extension[a]	4.2 ± 3.4	7.0 ± 3.3	0.012
	ROM[a]	96.2 ± 5.6	90.3 ± 3.8	< 0.001
Ankle	DF	33.7 ± 5.1	35.0 ± 6.6	0.789
	PF[a]	29.9 ± 5.0	22.1 ± 7.9	0.004
	ROM[a]	64.5 ± 3.9	59.1 ± 7.5	0.003
Hip	Adduction	7.8 ± 4.6	4.6 ± 4.6	0.108
	Abduction	9.1 ± 3.4	8.4 ± 3.6	0.084
	ROM	14.4 ± 4.0	14.7 ± 4.2	0.437
Knee	Abduction[a]	0.2 ± 5.6	3.2 ± 4.8	0.002
	Adduction	13.0 ± 16.1	21.6 ± 14.0	0.226
	ROM	16.5 ± 10.5	15.4 ± 11.7	0.630
Ankle	Adduction	4.8 ± 5.6	8.9 ± 6.1	0.108
	Abduction	1.1 ± 1.6	0.3 ± 1.0	0.084
	ROM	12.8 ± 3.6	12.8 ± 4.8	0.882

DF, dorsiflexion; PF, plantar flexion; ROM, range of motion.
[a] , $p < 0.05$, indicates a significance between males and females.

Table 3
Means and standard deviations for the peak joint moment (N·m·kg^{-1}) during stair ascent and descent in normal weight ($n = 19$), overweight ($n = 18$), and obese participants ($n = 8$).

Ascent	Normal	Overweight	Obese
Hip flexor[a]	0.26 ± 0.18	0.22 ± 0.17	0.42 ± 0.20[c]
Hip extensor	0.72 ± 0.17	0.70 ± 0.17	0.61 ± 0.20
Knee extensor	0.94 ± 0.29	1.05 ± 0.35	0.99 ± 0.33
Ankle PF	1.20 ± 0.23	1.25 ± 0.15	1.11 ± 0.12
Hip abductor	0.44 ± 0.18	0.35 ± 0.14	0.32 ± 0.18
Knee abductor	0.44 ± 0.19	0.40 ± 0.21	0.29 ± 0.13
Knee adductor	-0.15 ± 0.11	-0.13 ± 0.13	-0.09 ± 0.08
Ankle adductor	–	–	–
Ankle abductor	0.14 ± 0.10	0.16 ± 0.07	0.20 ± 0.06
Descent	**Normal**	**Overweight**	**Obese**
Hip flexor	0.26 ± 0.12	0.22 ± 0.09	0.27 ± 0.10
Hip extensor	0.04 ± 0.32	0.05 ± 0.39	0.03 ± 0.27
Knee extensor[a]	0.70 ± 0.29[b]	0.98 ± 0.30	0.86 ± 0.42
Ankle PF	1.03 ± 0.13	1.00 ± 0.18	1.03 ± 0.10
Hip abductor	0.82 ± 0.24	0.80 ± 0.21	0.63 ± 0.24
Knee abductor[a]	0.44 ± 0.25	0.52 ± 0.20	0.27 ± 0.20[c]
Knee adductor	-0.17 ± 0.17	-0.22 ± 0.15	-0.09 ± 0.11
Ankle adductor	-0.02 ± 0.23	-0.02 ± 0.026	-0.01 ± 0.02
Ankle abductor[a]	0.12 ± 0.08	0.09 ± 0.06	0.21 ± 0.11[b,c]

[a] , $p < 0.05$, indicates a significant effect of mass between normal, overweight, and obese.
[b] , $p < 0.05$, the normal weight vs. overweight group.
[c] , $p < 0.05$, the overweight vs. obese group.

influence on the joint moment ($F(34) = 1.836$, $p = 0.026$), irrespective of sex ($F(17) = 1.730$, $p = 0.110$). Considering that no interaction or effect of sex was found, the joint moment data for the males and females were pooled for the ANOVA and post-hoc tests. Table 3 lists the means and standard deviations for the peak joint moment of force during stair climbing for normal weight, overweight, and obese participants.

The peak hip flexor moment of the obese individuals showed significantly higher than the overweight group ($p = 0.031$) in ascent. In descent overweight group had a significantly larger knee extensor moment ($p = 0.026$) than the normal weight group, as well as a larger knee peak abductor moment than the obese group ($p = 0.036$). Moreover, the obese group had a significantly larger ankle abductor moment than the normal weight ($p = 0.031$) and overweight groups ($p = 0.002$).

Discussion

The purpose of this study was to examine the effects of body mass and sex on the kinematics and kinetics of the lower limb in normal weight, overweight, and obese participants during stair ascent and descent. The main findings from the study are 1) sex had a significant influence on peak joint angles and ROM during stair ascent and descent in older adults, whereas body mass did not have a significant influence on these variables; and 2) the peak joint moment of the lower limb was significantly influenced by the body mass during stair ascent and decent, irrespective of the effects of sex.

Concerning the kinematic findings, sex differences were found in the peak joint angles and ROM at the hip, knee and ankle in ascent and at the knee and ankle in descent. The females had significantly larger ankle plantar flexion angles during ascent and descent. However, their knee extension angles were smaller compared with the males. The sex differences in the knee peak extension and plantar flexion angles might be related to the body height difference between males and females. Livingston et al.[17] studied impact of body height, shorter 155.9 ± 2.1 cm, medium (163.5 ± 2.2 cm) and tall (171.6 ± 2.1 cm) on knee joint angles during stair climbing. They found that shorter participants would use larger knee flexion angles (92° to 105°) than taller participants whose angles would range from 83° to 96°, when climbing stairs. In the study females' body height was shorter than males. They may have been required to flex their knees more during descent to compensate for their shorter height. This activity resulted in a larger ROM at the knee during descent.

In the frontal plane, the differences in the frontal peak joint angles and ROM may reflect the changes in the participant's center of mass relative to the base of support.[18] During ascent, the females would adduct their ankles more than the males. And during descent, the females would not only adduct more in their ankles, but also in the knees compared with the males. These findings on the peak knee abduction angles were clinically important because they could provide a possible mechanism for knee OA development and may explain why women older than 50-years-old are at a higher risk of OA than men.[19,20] Researchers believed that the valgus misalignment (knock knees) at the knee, which resulted because of the larger Q angle in females, may lead to knee pain.[21] Research suggested that the varus malalignment (bowlegs knee) would cause higher loading on the medial compartment compared with the lateral compartment of the knee; this higher loading may lead to medial compartment OA.[22] Although the differences in the frontal joint angles may be clinically small, the change in the joint angle could be detrimental to the loading at the knee and may lead to long-term mobility problems, such as OA and valgus/varus deformities, for example "knock knee" and "bowleg" syndrome, in obese individuals.[12]

The present study revealed that the peak joint moments of force for the hip, knee, and ankle were influenced by the body mass. Sex did not have a significant influence on the peak joint moment of force. During ascent, the obese group demonstrated significantly greater hip flexor moment than the overweight group. This finding is consistent with findings that young obese participants had bigger hip flexion moment in ascent than young normal-weight participants.[7] The possible reason for the difference may be the position of the trunk. Gilleard and Smith (2007) studied body posture and hip joint moment in obese people during standing.[23] They found that obese adults had a more flexed trunk posture during standing and had increased hip joint moment compared to normal-weight people. The higher hip flexor moment in obese people in this study might be influenced by trunk posture and body mass, and will need to be considered in future analysis. At the knee level, the sagittal knee moments of the normal weight, overweight, and obese groups were consistent with the findings from other studies on stair ascent based on normal-weight population.[1–4]

In contrast to ascent, body mass had significant impact on joint moment at the knee and ankle in both sagittal and frontal planes in descent. The descent required a second peak extensor moment at the knee toward the lower body through flexion control at the knee.[3] Descent may place more loading at the knee, resulting in a higher moment caused by the force of gravity acting on the descending participant. Both overweight and obese participants had higher peak knee extensor moments than normal-weight participants. Notably, the overweight group had a significantly higher peak knee extensor moment than the normal weight group during descent (Table 3). And the overweight group showed significant higher knee abductor moment than the obese group. The significant differences between the overweight and normal group and between overweight and obese group might be related to altered muscle contractile function and body mass. Bollinger discussed the contribution of the muscle contractile dysfunction to biomechanics alterations in obesity based on the research evidences in the field.[24] Decreased relative muscle strength and altered contractile properties of the muscle is associated with obesity, which is linked to muscle contractile disfunction. Recently, Valenzuela and co-workers further provided supporting evidence to Bollinger's explanation.[25] Theirs study in 111 obese participants aged 45 to 74 with BMI 35–64 kg m^{-2} demonstrated a high prevalence of poor muscle quality (the expression of muscle function per unit of muscle mass) in obese people. And BMI was positively associated with the prevalence of poor muscle quality. In this study, the significantly higher knee abductor moment in the overweight group than obsess group might be related to their differences in BMI level and subsequently in the extent of poor muscle quality. The obese group might experience more negative changes in muscle quality than the overweight group and their muscles were unable to generate strong contractile force. When scaled to the body weight, the higher moments are strong indications of the higher loading of the musculoskeletal structures in obese individuals compared with normal-weight individuals. The higher joint loading at the knee may have several implications on the amount of stress acting on the articular cartilage of the knee. Cartilages in the knee joint are responsible for reducing the friction between the articular surfaces of the knee[29]. Although necessary loads are needed to stimulate the bone to obtain stronger and excessive bone tissue. However, these higher loads may also cause microdamage to the musculoskeletal tissues and lead to OA development.[12]

A limitation of this study is that it was conducted in a laboratory setting, which may not be conducive for stair climbing in the real world. The experimental staircase used consisted of only three steps, indicating that the participants accelerated or decelerated when on the force plate because no adequate time was available to develop a steady ascent or descent rate. In addition, one of the most pressing matters that have yet to be addressed by researchers in biomechanics research on obese individuals is the issue involving the movement of skin markers. The movement of the markers during the performance of the locomotion may lead to errors in the kinematic calculations, and subsequently, accuracy of the kinetic data. Thus far, no viable solution was available to minimize the errors from the skin markers by minimizing movement of the skin.

Conclusion

Body mass had a significant influence on joint kinetics during stair ascent and descent in older adults, mainly influencing the hip joint during stair ascent and mainly influence on the knee and ankle joint during descent. Overweight and obesity increase joint loading of lower limb during stair ascent and descent, generating bigger joint loading at the hip in ascent and resulting higher joint loading at the knee and ankle joint. Sex differences were present in the peak joint angles and ROM in both sagittal and frontal motion during ascent and descent. The females had higher knee adduction compared with the males during descent. The findings may be helpful to the understanding the higher risk of OA development in overweight and obese older adults as well as women.

Ethical approval statement

This study was approved by the University of Ottawa research ethics committee, and all participants were required to sign an informed consent form. Our study reported in the manuscript was done in accord with the Helsinki Declaration of 1975.

Submission statement

Authors declare that this work has not been published before and is not being considered for publication in another journal.

Conflict of interest

Authors confirm that there are no conflicts of interest associated with this publication.

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