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Correlation between rotational moments of the knee and other joints during gait, including the free moment of patients with a medial meniscus tear

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Purpose: Rotation of the knee puts stress on the medial meniscus and can be a factor in the progression of knee osteoarthritis. This study aimed to investigate the rotational moment (internal rotation and external rotation) of the knee during gait and relationship between the rotational moments of the knee and other joints, including the free moment during gait. *Methods*: We included 18 patients with medial meniscus tears (MM group) and 10 asymptomatic participants in this study. We performed 3D gait analysis. The internal ankle, knee, and hip rotational moments as well as free moment were compared between the groups. Additionally, we investigated correlations between rotational moments of the knee and other joints during gait. *Results*: The maximal knee external rotation moment in the MM group was smaller than that in the asymptomatic group ($p = 0.04$, $g = 0.76$); however, there were no significant differences in the maximal internal rotation moment between the groups ($p = 0.97$, $g = 0.02$). The internal rotation (external knee external rotation) moment positively correlated with the hip internal rotation moment ($p < 0.01$, $r = 0.69$) in the MM group. *Conclusions*: The internal rotation (passive knee external rotation moment) did not decrease sufficiently, and correlation was observed between moments of the knee and hip in the MM group, especially during the late stance phase of gait. Reducing these abnormal moments during gait through rehabilitation may be important in patients with medial meniscus tears to prevent rapid progression of knee osteoarthritis.

Key words: *gait, knee moment, free moment, medial meniscus tear*

1. Introduction

Medial meniscus (MM) tear of the knee causes swelling, pain and gait disorders [13], [19]. One of the causes of MM tears is related to medial compartmental degeneration in the middle-aged population [11], [32]. These tears induce rapid progression of knee osteoarthritis (OA) [19], [22] by concentrating and increasing compressive forces on the medial compartment of the knee [8], [26]. This lesion can occur during usual daily activities, such as stair descent, squatting and walking [11]. Since MM tears damage knee structures through mechanical stress, comprehending the movement pattern of repetitive daily activities, such as gait, is important to avoid inducing symptoms and rapid progression of knee OA [7].

Previous studies have used different methods to report movement patterns during gait, however, few studies have reported this in patients with MM tears. Using a motion capture system and a radiologic device, Marsh [22] investigated knee kinematics and estimated joint contact patterns, however, they focused only on the knee joint. Russell [27] investigated knee

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moment on the sagittal and frontal planes and found no significant differences between participants with and without meniscus lesions. Magyar [21] investigated the coefficient of variance values of spatiotemporal parameters during gait in patients with pre-meniscectomy and reported that gait complexity decreased. However, to the best of our knowledge, there are no reports that focus on rotational moment of the knee and other joints during gait in patients with MM tears. Stärke [28] reported that internal rotation (IR) of the femur increased resultant tension in the MM and external rotation (ER) decreased tension. Marsh [22] reported that ER movement of the knee caused the MM to move posteriorly, thereby adding additional stress to the joint. It was thought that the internal knee ER moment forces the knee to actively move in the ER direction. Moreover, the external knee ER moment (internal knee IR moment) was assumed to increase the mechanical stress by increasing passive forces on the MM. Given these facts, there is a potential relationship between rotational stress, which is caused by rotational moment, placed on the MM during gait and accelerated progression of knee OA.

Other reports have implied the importance of rotational movement in patients with early [12], [18], [23] and moderate [4], [5], [14], [17] stages of knee OA. Several studies concluded that altered rotational moment may be a factor in early knee OA development preceding the onset of symptoms [2], [5]. Ultimately, the property of rotational moment during gait in patients with MM tears remains unknown. Given that the rotational moment of knee joints is altered, it is important to investigate how other joints impact abnormal knee moment to inform rehabilitation approaches.

The free moment (FM) occurs due to friction between the ground and the foot [16], as shown in Fig. 1. Previous studies have reported that FM is related to tibial torsional stress [16], [24] which suggests that the FM may apply excessive mechanical stress to the knee via tibial rotation in patients with MM tears.

The purpose of this study was to determine whether the rotational moments of the knee become larger in patients with MM tears and to clarify the relationship between the rotational moments of the knee and other joints (ankle, hip and FM) during gait in patients with MM tears. We hypothesized that: (1) the magnitude of peak knee rotational moment would be larger in patients with MM tears than that in asymptomatic participants; (2) the group difference in peak knee ER moment would be more pronounced than that of the peak knee IR moment; and (3) knee rotation moments would be well-correlated with the FM in patients with MM tears.

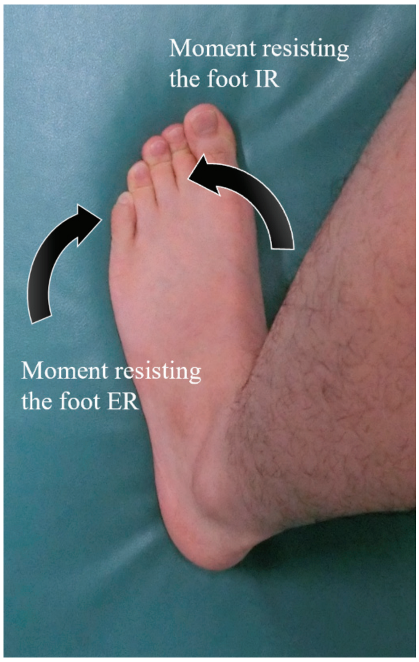

Fig. 1. Representation of the FM of the foot that resists the foot's IR and ER. FM – free moment, IR – internal rotation, ER – external rotation

2. Materials and methods

2.1. Participants

All participants were recruited from an orthopedic hospital. This study included 18 patients with MM tears (MM group: age of 60.2 ± 5.4 years, height of 1.57 ± 0.06 m, mass of 60.5 ± 8.8 kg) and 10 age- and sex-matched community-dwelling asymptomatic volunteers (asymptomatic group: age of 57.1 ± 4.5 years, height of 1.56 ± 0.04 m, mass of 49.4 ± 3.6 kg). The participants in the MM group were diagnosed with MM tear by expert orthopedic doctors using magnetic resonance imaging (MRI), and they underwent meniscectomy a few days after measurements. Other inclusion criteria of the MM group were female sex, ability to walk without the aid of medical equipment and age of 40–70 years. Patients with neurological conditions and other lower extremity joint disorders that affected gait were excluded. The asymptomatic group was composed of hospital staff. The inclusion and exclusion criteria for the asymptomatic group were the same as those of the MM group, with the exception of MM-related criteria.

All procedures were approved by the Oita University Medical Faculty Ethics Committee (approval number 1259-T2), and all participants provided informed consent prior to participating in this study. The experimental procedures were conducted in accordance with the Declaration of Helsinki.

2.2. Data collection

A three-dimensional motion capture system (VICON MX; Vicon Motion Systems, Oxford, UK) equipped with eight infrared cameras and a force plate (AccuGait; Advanced Mechanical Technology Industry, Boston, MA, USA) was used for kinematic and kinetic data collection. An infrared reflection marker was attached to all participants at 52 bony landmarks: the mid-point between the L4 and L5 spinous process, jugular notch, xiphoid process, 2nd and 10th thoracic spinous processes, left scapula body, both sides of the temple, lateral end of the superior nuchal line, tragus, acromion process, lateral and medial epicondyles, ulnar and radial styloid processes, head of the third metacarpal, mid-lower end of the rib bone on the body side, top of the iliac crest, posterior superior iliac spine, anterior superior iliac spine, superior aspect of the greater trochanter, lateral side of the thighs, medial and lateral joint spaces of the knees, lateral side of the lower legs, medial and lateral malleoli, head of the first and fifth metatarsals and calcaneal tuberosity. The spatial motions of the markers were captured using a sampling rate of 100 fps. Simultaneously, ground reaction forces were measured using a force plate.

2.3. Gait task

The participants were asked to walk through a 10 m-long walkway at a comfortable speed. The force plate at the center of the walkway length was set on the affected side of patients in the MM group and on right side for participants in the asymptomatic group. These trials were repeated until the participants completed them at least 10 times with no missteps on the force plate.

2.4. Data analysis

First, the data collected using the motion capture system were filtered with a cutoff frequency of 6 Hz for kinematic data and 20 Hz for floor reaction forces [30]. Next, the positions of the joint centers at the hip, knee and ankle were approximated according to previous reports [1]. The knee joint angle and internal joint moments of the ankle, knee and hip were then calculated using the processing software BodyBuilder (Vicon Motion Systems, Oxford, UK) according to previous reports [1]. In particular, the rotational moments at each joint were calculated with the moment occurring along the vertical axis of each coordinate system. The FM that resisted the foot ER and IR was calculated in accordance with previous reports [16], [24]. All moment data were normalized by body mass [kg].

During this study, only the stance phase of the gait cycle was analyzed. The timings of initial contact and toe-off during the gait cycle were detected with a threshold of 10 N of the force plate. The gait speed was calculated from the quotient of the path length of the body mass' center in the anterior–posterior direction and the time taken for the stance phase.

The time of each stance phase was normalized to a 101-point scale. The peak values of the joint IR and ER moments and FM were calculated. Additionally, the range of moments (the difference between the highest and lowest) during the stance phase was calculated. The variables of the 10 trials were averaged, and the average values were used for the statistical analysis.

Data analyses were performed using MATLAB R 2017b (MathWorks, Natick, USA).

2.5. Statistical analysis

Anthropometric data, gait speed, and each direction's peak value, and the range of moments were checked for normality using the Shapiro–Wilk test. When data were not normally distributed, the Mann–Whitney test was used for comparison between the groups. For normally distributed data, we used the Welch test or a two-sample *t*-test, as appropriate, according to homoscedasticity. We also calculated Hedges' g as the effect size. Since gait speed and body mass differed significantly between the MM and asymptomatic groups, we performed the analysis of covariance (ANCOVA) with gait speed as a covariate and calculated η^2 as the effect size (moments were normalized by body mass). In this scenario, the rotational moments of the hip, knee and ankle as well as the force moment were established as the dependent variables, with the group being identified as the independent variable and gait speed serving as the covariate. We verified the ANCOVA assumptions of parallelism between: medial meniscus and control groups and a linear relationship between the moment variables and gait speed. As a result, only the peak values and ranges of the hip ER moment did had prerequisites. We used the ANCOVA for this parameter.

Additionally, correlation coefficients r between peak rotational moments of the knee and other joints, including the FM, were calculated for each group both with gait speed as a covariate. The peak IR and ER values were used for the correlation analyses. The significance level for all statistical tests was set at 5%. Statistical analyses were performed using SPSS 17.0 J for Windows (IBM Corp., Armonk, NY).

3. Results

3.1. Anthropometric and gait speed data

The anthropometric and gait speed data of MM and asymptomatic groups are shown in Table 1. The body mass was significantly larger in the MM group than in the asymptomatic group (p = 0.010, g = 1.418). The gait speed was significantly slower in the MM group than in the asymptomatic group (p = 0.046, g = 0.601).

Table 1. Anthropometric and gait speed data of MM and asymptomatic groups

Parameter	MM	Asymptomatic	p	g
Age [year]	60.2 (5.4)	57.1 (4.5)	0.141	0.535
Body mass [kg]	60.5 (8.8)	49.4 (3.6)	**0.010**	**1.418**
Body height [m])	1.57 (0.06)	1.56 (0.04)	0.913	0.142
Kellgren and Lawrence Grade (I/II/III/IV) [n]	2/14/2/0		–	
Gait speed (m/s)	0.99 (0.12)	1.09 (0.14)	**0.046**	**0.601**

Data are represented as means (SD). The significant differences are shown in bold text. MM – medial meniscus.

3.2. Moments

The FM and each internal joint moment for the MM and asymptomatic groups are shown in Table 2. The FM range was significantly smaller in the MM group than in the asymptomatic group (p = 0.014, g = 0.843). The IR moment of the ankle was significantly smaller in the MM group than in the asymptomatic group (p = 0.037, g = 0.726). For knee joints, the knee ER moment (p = 0.040, g = 0.758) and range (p = 0.021, g = 0.847) were significantly smaller in the MM group than in the asymptomatic group. There were no significant differences in hip joints between the two groups (ER moment: p = 0.832, g = 0.002, IR moment: p = 0.357, g = 0.343, range: p = 0.487, η^2 = 0.020).

3.3. Average time-series data

The average time-series data are shown in Figs. 2 and 3. The average time-series data of the knee rotation angle in the MM group showed similar pattern to that of the asymptomatic group in the first half of stance whereas it did not show the steep changes observed in the asymptomatic group in the second half of the stance (Fig. 2). The average time-series data of FM in the MM group showed that the amplitude of the signal was small (Fig. 3). The FM resisting the foot ER peaked between 90–100% and 70–80% of the signal for the MM and asymptomatic groups, respectively. The other time-series data did not show any outstanding features.

Table 2. The FM and each joint internal moment of MM and asymptomatic groups

Parameter	MM	Asymptomatic	p	g
FM [Nm/kg × 10^{-2}]				
Resisting the foot ER	2.6 ± 1.4	2.9 ± 1.5	0.571	0.166
Resisting the foot IR	5.5 ± 2.1	6.5 ± 1.6	0.187	0.417
Range	8.0 ± 1.2	9.4 ± 1.5	**0.014**	**0.843**
Ankle [Nm/kg × 10^{-2}]				
ER	27.2 ± 4.3	25.1 ± 9.9	0.454	0.266
IR	5.5 ± 2.2	7.3 ± 1.6	**0.037**	**0.726**
Range	32.6 ± 5.8	32.4 ± 8.7	0.922	**0.**026
Knee [Nm/kg × 10^{-2}]				
ER	12.3 ± 5.3	16.9 ± 5.4	**0.040**	**0.758**
IR	14.5 ± 5.5	14.6 ± 4.6	0.965	0.017
Range	26.8 ± 4.4	31.5 ± 5.4	**0.021**	**0.847**
Hip [Nm/kg×10^{-2}]				
ER	15.2 ± 4.8	16.7 ± 3.2	0.832	0.002*
IR	14.9 ± 5.4	17.0 ± 5.4	0.357	0.343
Range	30.1 ± 5.5	33.6 ± 4.9	0.487	0.020*

Data are represented as means ± SD. The significant differences are shown in bold text. * – η^2 was used as the effect size for hip ER moment and range. IR – internal rotation, ER – external rotation, MM – medial meniscus, FM – free moment.

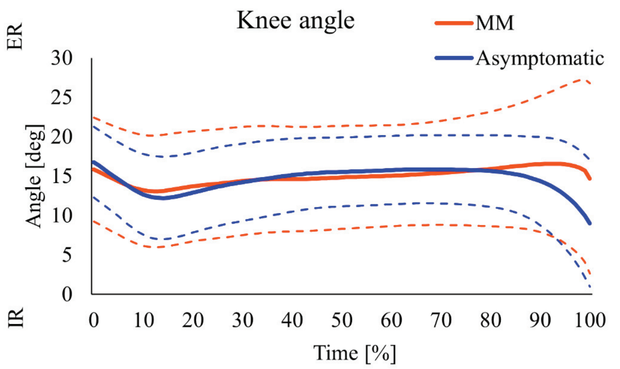

Fig. 2. Time-series data of knee rotational angle of the MM and asymptomatic groups. The vertical axis indicates the amount of angle and the horizontal axis indicates the time of stance phase. The red line represents the MM group and the blue line represents the asymptomatic group. The solid line represents the mean value and the broken line represents the one standard deviation. MM – medial meniscus

Table 3. The correlation matrix of the internal knee moments and the other moments in each group adjusted with the gait speed as covariance

		MM		Asymptomatic	
		Knee ER moment	Knee IR moment	Knee ER moment	Knee IR moment
FM	Resisting foot ER	–0.458 (0.064)	0.232 (0.370)	–0.065 (0.868)	0.513 (0.158)
	Resisting foot IR	0.529 (**0.029**)	–0.256 (0.321)	0.173 (0.656)	–0.123 (0.753)
Ankle	ER moment	0.080 (0.762)	0.186 (0.476)	0.188 (0.628)	0.004 (0.992)
	IR moment	0.579 (**0.015**)	–0.398 (0.113)	–0.073 (0.853)	–0.242 (0.531)
Hip	ER moment	0.457 (0.065)	–0.509 (**0.037**)	0.432 (0.246)	–0.501 (0.170)
	IR moment	–0.480 (0.051)	0.686 (**0.002**)	–0.318 (0.405)	0.781 (**0.013**)

Data are represented as correlation coefficient r (significance probability p). Significantly correlations are showed as bold text. FM – free moment, ER – external rotation, IR – internal rotation, MM – medial meniscus.

3.4. Correlations between the knee rotation moment and other moments

The correlation between the knee rotation moment and other moments in each group is shown in Table 3, with respect to the gait speed covariate. In the MM group, the knee ER moment was positively correlated with the FM and ankle IR moment. The p values for negative correlation between the knee ER moment and hip IR moment in the MM group was not less than 0.05,

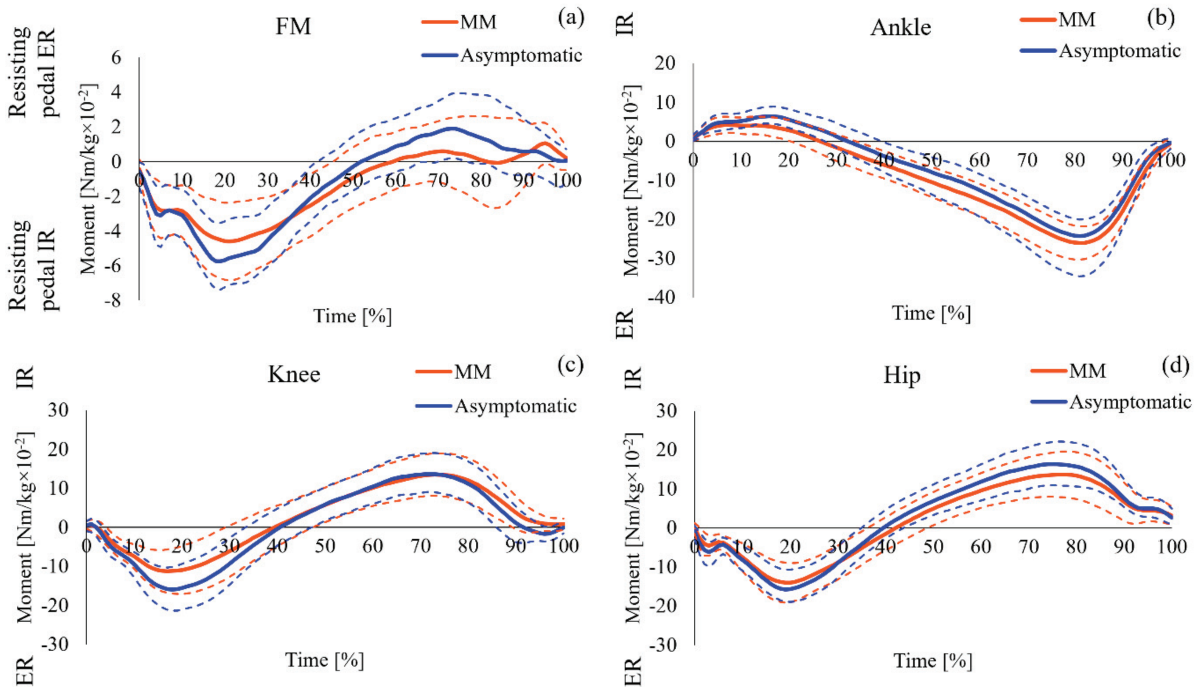

Fig. 3. Time-series data of each rotational moment of the MM and asymptomatic groups. The vertical axis indicates the amount of moment and the horizontal axis indicates the time of stance phase.
The red line represents the MM group and the blue line represents the asymptomatic group. The solid line represents the mean value and the broken line represents the one standard deviation. Each graph shows the (a) FM and (b) ankle, (c) knee, and (d) hip rotational moment. MM – medial meniscus; FM – free moment

but it was considerably small, so that they nearly breached the threshold. The knee IR moment was negatively correlated with hip ER moments and positively correlated with hip IR moments. In the asymptomatic group, the knee IR moment was positively correlated with the hip IR moment.

4. Discussion

This study investigated the rotational moments of each joint, including FM, in patients with MM tears and asymptomatic participants. We hypothesized that: (1) the magnitude of knee rotation moments would be larger in the MM group; (2) the group difference in knee ER moment would be more pronounced than that of the knee IR moment; and (3) knee rotation moments would be well-correlated with the FM in the MM group. However, our hypotheses were refuted. It was postulated that the internal knee ER moment forces the knee to actively move in the ER direction. Moreover, the external knee ER moment (internal knee IR moment) was assumed to increase the mechanical stress by increasing passive forces on the MM. We found that there were no significant differences in the internal knee IR moments between the MM and asymptomatic groups; furthermore, the internal ER moment and range were decreased (Table 2). These facts indicated that, in the MM group, the knee ER moment was decreased but the passive moment (internal knee IR moment) did not decrease sufficiently. Therefore, knee rotational stress increased relatively. These results agree with those of a previous study on patients with knee OA [14]. Because the internal IR moment applies stress to the MM more passively by the tibial ER relative to thigh IR, it was assumed that patients in the MM group were not able to adjust their walking pattern to avoid the stress. It was initially thought that this finding might simply be due to reduced activation of the muscles contributing to the knee IR without a concomitant increase in activation of the muscles contributing to the knee ER. However, the constant and comparable knee angle to the asymptomatic group at the same time (70–80% of stance phase) negates this notion.

It was assumed that whether patients with MM tears feel pain depends on the injured area of the MM. The inner third of the MM is known as the "white–white zone" and outer third as the "red–red zone" [3], [9]. The white–white zone rarely has free nerve endings and arteries, while the red–red zone is rich [7] in nerve endings and arteries. Progression of MM tears to the red–red zone will cause knee pain. In the current study, we recruited patients who underwent either partial meniscectomy or repair for their knee pain a few days after measurement. They may have repeated the gait patterns with greater knee IR moments (external ER moment), which may result in progression to painful conditions.

During the second half of stance, the knee experienced an internal IR moment, the ankle an internal ER moment, the hip an internal IR moment and the FM resisted the foot ER. During these moments, the knee IR moment positively correlated with hip IR moment in both groups. This meant that the correlation between the knee and hip IR moments was not a phenomenon specific to the gait of patients with MM tears. However, the knee IR moment negatively correlated with the hip ER moment only in the MM group whereas no correlation was observed in the asymptomatic group. This result indicated that the change in gait strategy in the early stance phase affected the late stance phase. Astephen [4] also reported that greater knee IR moment was coupled with reduced hip ER moment in patients with moderate knee OA during gait. This abnormal relationship may be a risk of rapid knee OA progression which may be altered through rehabilitation.

In patients with symptomatic MM tears, Luc-Harkey [20] reported that weakness of the quadriceps and hamstring muscles was associated with subjective and objective clinical features, and patients with weakened muscles experienced more pain and difficulty while performing daily activities. Becker [6] and Sturnieks [29] reported quadriceps muscle weakness after arthroscopic partial meniscectomy. Magyar [21] reported that patients who underwent pre-meniscectomy showed reduced variability in knee and hip motions. Hip and knee muscle weakness have also been reported in patients with knee OA [10], [15], [31]. These studies reported that knee extensor and hip abductor muscle strength were associated with functional performance. These reports also implied the presence of knee and hip muscle weakness was likely in patients with MM. Moreover, these patients may not have been able to move their hips to avoid stress induced by MM because of hip muscle weakness. Since there were no data on muscle strength in the current study, further research is needed to assess the relationship between knee rotational moment and hip muscle strength.

During the first half of stance, the knee experienced an internal ER moment, the ankle an internal IR moment, the hip an ER moment and the FM resisted the foot IR. The knee ER moment was significantly lower in the MM group than in the asymptomatic group, and the knee ER moment correlated with the ankle IR moment and FM resisting foot IR in the MM group. The knee ER moment also tended to correlate negatively with the hip IR moment. These results implied that the MM group avoided exerting the knee ER moment, and they could not utilize the floor reaction force for the forward progression of their body using frictional force. Astephen [4] reported that patients with moderate knee OA had smaller hip IR moments and similar knee ER moments in the first half of stance. This difference may be due to differences in pathology or severity. This reduced progression force appeared to be the cause of the slower gait speed and excessive increase in FM resisting the foot ER in 90–100% of the gait (Fig. 3a). These phenomena were compensation strategies for the loss of progression force. Patients in the MM group might have attempted to twist their lower limb to create progression force by externally rotating their hip (by exerting internal hip IR moment caused by eccentric contraction) and generating the FM resisting the foot ER within a short period. This is surmised by the waveform of the hip moment in 90–100% of the stance phase. However, this strategy should be avoided because it may also increase the external knee ER moment. As their pathology worsens, they may tend to reverse the hip IR moment to ER moment to avoid the rotational stress, as described in a previous study of patients with moderate knee OA [4].

This study had some limitations. First, the asymptomatic group was not evaluated using MRI, which means the possibility that they may have had asymptomatic MM tears in their knees cannot be dismissed. Second, the number of patients in the asymptomatic group was smaller than that in the MM group. Therefore, these results should be interpreted carefully. Third, the MM group may have been affected by the coexistence of osteoarthritis, which can alter changes in gait patterns. Finally, only rotational moments during gait were investigated in the current study, and there may be other factors resulting in differences between the MM and asymptomatic groups, such as sagittal or frontal plane moments or compression force calculated with finite element analysis. Thus, a more detailed analysis is required. Although there were some limitations, this study showed the possibility about the aggravation of the disease condition by the compensation strategy to produce the force that moves the body forward. In the rehabilitation approaches, it seems to be important to reconstruct the body function (such as strengthen the hip IR and extension muscle) for forward progression of the body without the torsional movement in terminal stance.

5. Conclusions

We found that patients with MM tears showed a reduction in ER moment and that patients may have avoided utilizing their knee to exert internal ER moment. However, the external ER moment was not decreased and there was a possibility that patients with MM tears applied external rotational stress to their MM which may worsen their condition through repetitive gait patterns. Moreover, the reduction in knee moment was accomplished by the reduction in FM and ankle IR moment. Such compensational movements cause overload that worsens joint health. These results provide a detailed understanding of the gait patterns of patients with MM tears which may be helpful for constructing rehabilitation protocols.

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References

[1] Anan M., Hattori H., Tanimoto K., Wakimoto Y., Ibara T., Kito N., Shinkoda K., *The coordination of joint movements during sit-to-stand motion in old adults: the uncontrolled manifold analysis*, Phys. Ther. Res., 2017, 20 (2), 44–50.

[2] Andriacchi T.P., Mundermann A., *The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis*, Curr. Opin. Rheumatol., 2006, 18 (5), 514–518.

[3] Arnoczky S.P., Warren R.F., *Microvasculature of the human meniscus*, Am. J. Sports Med., 1982, 10 (2), 90–95.

[4] Astephen J.L., Deluzio K.J., Caldwell G.E., Dunbar M.J., Hubley-Kozey C.L., *Gait and neuromuscular pattern changes are associated with differences in knee osteoarthritis severity levels*, J. Biomech., 2008, 41 (4), 868–876.

[5] Astephen Wilson J.L., Hatfield G., Stanish W.D., Hubley-Kozey C.L., *Asymptomatic individuals with radiographic evidence of knee osteoarthritis walk with different knee mechanics patterns than symptomatic individuals with the same radiographic evidence*, Osteoarthritis Cartilage, 2013, 21, S49–S50.

[6] Becker R., Berth A., Nehring M., Awiszus F., *Neuromuscular quadriceps dysfunction prior to osteoarthritis of the knee*, J. Orthop. Res., 2004, 22 (4), 768–773.

[7] Bhattacharyya T., Gale D., Dewire P., Totterman S., Gale M.E., *The clinical importance of meniscal tears demonstrated by magnetic resonance imaging in osteoarthritis of the knee*, J. Bone Joint Surg., 2003, 85 (1), 4–9.

[8] CARTER T. E., TAYLOR K.A., SPRITZER C.E., UTTURKAR G.M., TAYLOR D.C., MOORMAN C.T. 3rd, GARRETT W.E., GUILAK F., MCNULTY A.L., DEFRATE L.E., *In vivo cartilage strain increases following medial meniscal tear and correlates with synovial fluid matrix metalloproteinase activity*, J. Biomech., 2015, 48 (8), 1461–1468.

[9] CHAHLA J., CINQUE M.E., GODIN J.A., GEESLIN A.G., MOATSHE G., LAPRADE R.F., *Review of Arnoczky and Warren on the microvasculature of the human meniscus*, J. Isakos, 2017, 2 (4), 229–232.

[10] COSTA R.A., OLIVEIRA L.M., WATANABE S.H., JONES A., NATOUR J., *Isokinetic assessment of the hip muscles in patients with osteoarthritis of the knee*, Clinics, 2010, 65 (12), 1253–1259.

[11] FURUMATSU T., OKAZAKI Y., OKAZAKI Y., HINO T., KAMATSUKI Y., MASUDA S., MIYAZAWA S., NAKATA E., HASEI J., KUNISADA T., OZAKI T., *Injury patterns of medial meniscus posterior root tears*, Orthop. Traumatol. Surg. Res., 2019, 105 (1), 107–111.

[12] GÖK H., ERGIN S., YAVUZER G., *Kinetic and kinematic characteristics of gait in patients with medial knee arthrosis*, Acta Orthop. Scand., 2002, 73 (6), 647–652.

[13] GREIS P.E., BARDANA D.D., HOLMSTROM M.C., BURKS R.T., *Meniscal injury: I. Basic science and evaluation*, J. Am. Acad. Orthop. Surg., 2002, 10 (3), 168–176.

[14] HARDING G.T., HUBLEY-KOZEY C.L., DUNBAR M.J., STANISH W.D., ASTEPHEN WILSON J.L., *Body mass index affects knee joint mechanics during gait differently with and without moderate knee osteoarthritis*, Osteoarthritis cartilage, 2012, 20 (11), 1234–1242.

[15] HINMAN R.S., HUNT M.A., CREABY M.W., WRIGLEY T.V., MCMANUS F.J., BENNELL K.L., *Hip muscle weakness in individuals with medial knee osteoarthritis*, Arthritis Care Res., 2010, 62 (8), 1190–1193.

[16] HOLDEN J.P., CAVANAGH P.R., *The free moment of ground reaction in distance running and its changes with pronation*, J. Biomech., 1991, 24 (10), 887–897.

[17] KAUFMAN K.R., HUGHES C., MORREY B.F., MORREY M., AN K.N., *Gait characteristics of patients with knee osteoarthritis*, J. Biomech., 2001, 34 (7), 907–915.

[18] LANDRY S.C., MCKEAN K.A., HUBLEY-KOZEY C.L., STANISH W.D., DELUZIO K.J., *Knee biomechanics of moderate OA patients measured during gait at a self-selected and fast walking speed*, J. Biomech., 2007, 40 (8), 1754–1761.

[19] LANGE A.K., FIATARONE SINGH M.A., SMITH R.M., FOROUGHI N., BAKER M.K., SHNIER R., VANWANSEELE B., *Degenerative meniscus tears and mobility impairment in women with knee osteoarthritis*, Osteoarthritis Cartilage, 2007, 15 (6), 701–708.

[20] LUC-HARKEY B.A., SAFRAN-NORTON C.E., MANDL L.A., KATZ J.N., LOSINA E., *Associations among knee muscle strength, structural damage, and pain and mobility in individuals with osteoarthritis and symptomatic meniscal tear*, BMC Musculoskelet. Disord., 2018, 19 (1), 258.

[21] MAGYAR M.O., KNOLL Z, KISS R.M., *The influence of medial meniscus injury and meniscectomy on the variability of gait parameters*, Knee Surg. Sports Traumatol. Arthrosc., 2012, 20 (2), 290–297.

[22] MARSH C.A., MARTIN D.E., HARNER C.D., TASHMAN S., *Effect of Posterior Horn Medial Meniscus Root Tear on In Vivo Knee Kinematics*, Orthop. J. Sports Med., 2014, 2 (7), 2325967114541220.

[23] MEIRELES S., WESSELING M., SMITH C.R., THELEN D.G., VERSCHUEREN S., JONKERS I., *Medial knee loading is altered in subjects with early osteoarthritis during gait but not during step-up-and-over task*, PloS one, 2017, 12 (11), e0187583.

[24] MILNER C.E., DAVIS I.S., HAMILL J., *Free moment as a predictor of tibial stress fracture in distance runners*, J. Biomech., 2006, 39 (15), 2819–2825.

[25] MINE T., KIMURA M., SAKKA A., KAWAI S., *Innervation of nociceptors in the menisci of the knee joint: an immunohistochemical study*, Arch. Orthop. Trauma Surg., 2000, 120 (3–4), 201–204.

[26] PEÑA E., CALVO B., MARTÍNEZ M.A., PALANCA D., DOBLARÉ M., *Finite element analysis of the effect of meniscal tears and meniscectomies on human knee biomechanics*, Clin. Biomech., 2005, 20 (5), 498–507.

[27] RUSSELL C., PEDOIA V., SOUZA R.B., MAJUMDAR S., *Cross-sectional and longitudinal study of the impact of posterior meniscus horn lesions on adjacent cartilage composition, patient-reported outcomes and gait biomechanics in subjects without radiographic osteoarthritis*, Osteoarthritis Cartilage, 2017, 25 (5), 708–717.

[28] STÄRKE C., KOPF S., LIPPISCH R., LOHMANN C.H., BECKER R., *Tensile forces on repaired medial meniscal root tears*, Arthroscopy, 2013, 29 (2), 205–212.

[29] STURNIEKS D.L., BESIER T.F., HAMER P.W., ACKLAND T.R., MILLS P.M., STACHOWIAK G.W., PODSIADLO P., LLOYD D.G., *Knee strength and knee adduction moments following arthroscopic partial meniscectomy*, Med. Sci. Sports Exerc., 2008, 40 (6), 991–997.

[30] TATEUCHI H., KOYAMA Y., AKIYAMA H., GOTO K., SO K., KURODA Y., ICHIHASHI N., *Radiographic and clinical factors associated with one-leg standing and gait in patients with mild-to-moderate secondary hip osteoarthritis*, Gait Posture, 2016, 49, 207–212.

[31] TEVALD M.A., MURRAY A., LUC B.A., LAI K., SOHN D., PIETROSIMONE B., *Hip abductor strength in people with knee osteoarthritis: A cross-sectional study of reliability and association with function*, Knee, 2016, 23 (1), 57–62.

[32] ZHANG K., LI L., YANG L., SHI J., ZHU L., LIANG H., WANG X., YANG X., JIANG Q., *Effect of degenerative and radial tears of the meniscus and resultant meniscectomy on the knee joint: a finite element analysis*, J. Orthop. Translat., 2019, 18, 20–31.