

Study on the Effects of Different Stair-Descending Methods on Knee Angle, Joint Moment and Joint Force

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Abstract. [Purpose] In general, people with bilateral osteoarthritis descend stairs sideways or backwards as compensatory movements. However, to the best of our knowledge, no studies have investigated these movements. The objective of the present study was to ascertain the effects of descending forwards and descending backwards on kinetic changes in the knee joint, to ascertain the optimal stair descending method for minimizing stress on the knee joint. [Subjects] Subjects were 30 adult women with no orthopedic or neurological disorders. [Methods] With step heights (riser heights) of 10, 15, 20 and 25 cm, changes in knee flexion angle, extension moment and joint force were measured when descending forwards and descending backwards using a three dimensional motion analysis system. [Results] Peak knee flexion angle, peak knee extension moment and peak knee joint forces observed in descending stairs backwards were smaller than those in the descending forwards action. [Conclusion] The present results suggest that descending stairs backwards for osteoarthritis patients is effective in protecting the knees, alleviating pain and acquiring compensatory movements.

Key words: 3-dimensional motion analysis, Osteoarthritis of the knee, Joint force

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INTRODUCTION

Treatment for osteoarthritis (OA) can be roughly divided into operative and conservative (including pharmacotherapy), and treatment selection is based on patient age, knee function and activities of daily life (ADL). As a general rule, conservative treatments are performed to prevent OA from progressing and to alleviate inflammation and pain, with provision of lifestyle guidance, including weight loss, exercise therapy, pharmacotherapy and brace therapy. Conversely, operative treatments for OA include arthroscopic debridement, high tibial osteotomy (HTO), unilateral knee arthroplasty

(UKA), and total knee arthroplasty (TKA), and exercise therapy is performed before and after surgery, with lifestyle guidance provided to protect both operative and non-operative joints. Lifestyle guidance is thus important for OA patients receiving both conservative and operative treatments. Such guidance can include setting up a Western-style living environment, avoiding sitting on the floor in the Japanese style or kneeling, and minimizing the use of stairs^{1,2)}. However, in Japan, living spaces are often narrow, and stairs are frequently used in and out of homes. Patients thus need to acquire stair ascending and descending skills to expand their range of activities and

promote independence in ADL. Epidemiological studies and kinematic assessments have investigated stair ascending and descending^{3,4}, finding that muscle activities for stair ascending and descending are greater than those for walking⁵, and joint stress is greater⁶. Stair ascending and descending are thus very difficult movements for elderly and disabled individuals⁷. In particular, many OA patients complain of knee pain while descending stairs⁸. As a general rule, when symptoms are unilateral, patients are instructed to descend one step at a time and lower the affected leg first to reduce joint stress⁹. However, many OA patients experience pain in both legs, and establishing methods to reduce joint stress on the supporting (following) leg is thus important. In general, people with bilateral OA descend backwards. Based on the assumption that such compensatory movements may offer some mechanical advantages, we investigated knee flexion angle and knee extension moment during descending backwards as documented in past studies¹⁰. The present study focused on changes in joint force during descending backwards.

SUBJECTS AND METHODS

Subjects

Subjects were 30 healthy adult women of average height (height, 154.1 ± 4.9 cm; body weight, 45.7 ± 3.9 kg; age, 20.3 ± 0.9 years) with no orthopedic or neurological disorders. Only women were enrolled to eliminate gender differences, as OA often affects women. Furthermore, since OA often affects women ≥ 40 years old, subjects included Japanese women with the same average height as Japanese women 40–60 years of age¹¹. Prior to the start of the study, informed consent was obtained after thoroughly explaining the study objectives and methods. The present study was conducted based on the Declaration of Helsinki and was approved by the ethics committees of Kosei General Hospital and Hiroshima Prefectural University.

Methods

The stairs used in the present study had six steps with a tread width of 30 cm and a riser height of 10, 15, 20 or 25 cm. These riser heights correspond to those generally found in Japan (10 cm for communal facilities such as movie theaters and concert halls; 15 and 20 cm for the average type of

Japanese house; 25 cm for the *agarikamachi* [a piece of wood at the front edge of the entranceway floor of Japanese houses] and for bus stepwells). For each riser height, there were four sets of stairs. Each set contained sections of three steps. The sections were separated five mm to prevent interference between the force plates. In addition, a non-slip mat was placed on the force plates so that none of the stairs would come in contact with each other. The stairs were made to match the size of the force plate and the dummy force plate, and was comprised of four parts: anterior left; anterior right; posterior left; and posterior right¹².

The present study used a three dimensional motion analysis system comprising a VICON 512 infrared position sensor (six cameras; Oxford Metrics, UK) and a force plate (Kistler, Switzerland) with sampling frequencies set at 120 and 1,080 Hz.

In this study, infrared reflection markers were attached to 12 areas on each subject: top of the head; left and right greater trochanters; lateral epicondyles of both knees; left and right lateral malleoli; left and right fifth metatarsal heads; and left inferior angle of the scapula (left/right-differentiation markers). Each subject was asked to start in a static standing position at the top of the stairs, and begin descending on a signal. The subject performed either forward descending (FD) or backward descending (BD) at a self-selected speed. Riser heights and descending methods were randomized, and each time the riser height was changed, the subject practiced descending, and then measurements were made. Under each condition, three measurements were made. Each time the riser height was changed, a break of about three min was provided. The study was conducted with the subjects barefoot to mirror normal activities in Japanese homes. Measurements were done on the left leg.

ARMO software (Gsport, Tokyo, Japan) was used for data analysis and extraction (Fig. 1-a, 1-b). The following parameters were measured for the supporting leg during stair-descending: joint force generated during the beginning of the stance (loading response) phase (JF1); initial knee flexion angle during the beginning of the stance phase (A1); knee extension moment during the beginning of the stance phase (M1); maximum joint force generated during the stance phase (JF2); knee flexion angle during the stance phase (A2 - simultaneous to JF2);

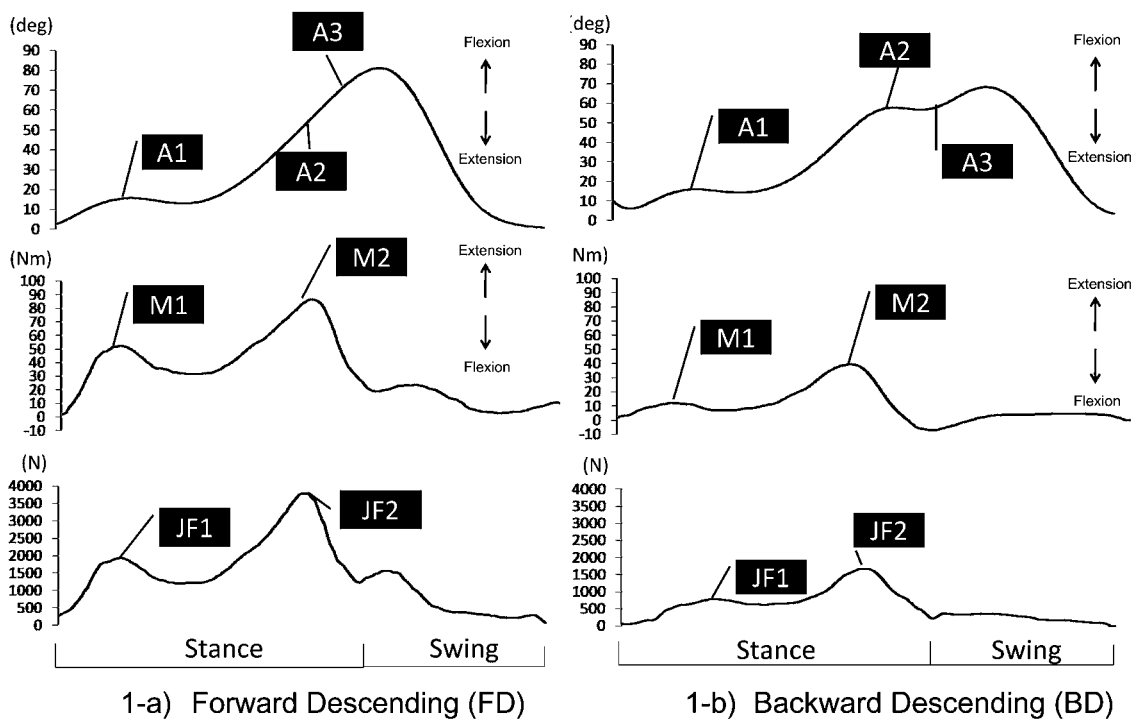


Fig. 1. Extraction points.

1-a) Forward Descending (FD). The loading responses for A1, M1, JF1, are shown. The parameters for A2, M2, JF2, when weight bearing and controlling the downward movement of the body are shown. The maximum value for knee flexion during stance is shown at A3. 1-b) Backward Descending (BD). The extraction points are the same as in FD.

knee extension moment during the stance phase (M2 - simultaneous to JF2); and maximum knee flexion angle during the stance phase (A3). The sum of the joint forces generated during a stance phase (ΣJF : summation of joint force) was also calculated. Based on inverse dynamics, joint force in the present study was calculated using a method for calculating the sum of muscle tension for periarticular muscles of the knee according to the Newton-Euler equation of motion¹³.

The data for joint force and moment were standardized to accommodate a different body weight.

For statistical analyses, paired t-tests were used to compare descending methods at each riser height. Values of $p < 0.05$ were considered statistically significant.

RESULTS

The knee flexion angle was smaller during BD. Significant differences were seen in A1 with 20 and

25 cm riser heights. Significant differences were seen in A2 with riser heights of 15, 20 or 25 cm. Significant differences were seen in A3 with all riser heights (Table 1).

The knee extension moment was smaller during BD. For both M1 and M2, significant differences were seen with all riser heights (Table 2).

The joint force was smaller during BD. Significant differences were seen in JF1 with riser heights of 15, 20 or 25 cm. With JF2 and ΣJF , significant differences were seen with all riser heights (Table 3).

DISCUSSION

Knee angles A1, A2 and A3 were smaller for BD than for FD. Tarabichi et al.¹⁴ reported that the mean knee flexion angle for OA patients ranged from 75° to 155° and that following a TKA ranged from about 115° to 150°. However, according to Walker et al., the usable knee flexion angle within ADLs (mean, 89.7°) was smaller than the passive

Table 1. Knee flexion angle (A1, A2, A3): average values

	A1		A2		A3	
	FD	vs BD	FD	vs BD	FD	vs BD
10 cm	15.6 ± 6.2	15.8 ± 7.1	40.4 ± 8.9	38.4 ± 8.1	65.7 ± 8.2	43.4 ± 7.5***
15 cm	20.8 ± 8.0	19.0 ± 7.4	54.1 ± 9.5	48.0 ± 8.9**	79.4 ± 9.5	53.8 ± 7.6***
20 cm	25.3 ± 7.9	21.8 ± 8.5**	68.9 ± 10.2	57.4 ± 9.4**	92.9 ± 8.0	63.7 ± 7.4***
25 cm	29.2 ± 9.1	24.3 ± 9.7**	80.8 ± 13.6	66.0 ± 8.9**	101.9 ± 7.0	73.6 ± 5.7***

*p<0.05; **p<0.01; ***p<0.001(deg)

Table 2. Knee extension moment (M1, M2) : average values

	M1		M2	
	FD	vs BD	FD	vs BD
10 cm	0.6 ± 0.3	0.5 ± 0.3*	1.2 ± 0.3	0.8 ± 0.3***
15 cm	0.8 ± 0.4	0.6 ± 0.3***	1.5 ± 0.3	0.9 ± 0.2***
20 cm	1.1 ± 0.4	0.7 ± 0.4***	1.7 ± 0.4	1.0 ± 0.2***
25 cm	1.1 ± 0.5	0.9 ± 0.4**	1.7 ± 0.4	1.0 ± 0.2***

*p<0.05; **p<0.01; ***p<0.001 (Nm/kg)

Table 3. Knee joint force (JF1, JF2, ΣJF) : average values

	JF1		JF2		ΣJF	
	FD	vs BD	FD	vs BD	FD	vs BD
10 cm	32.2 ± 13.9	29.8 ± 12.6	57.4 ± 12.4	40.8 ± 10.5***	3459.8 ± 950.5	3098.1 ± 893.5*
15 cm	42.8 ± 15.1	35.1 ± 14.1**	76.3 ± 17.2	50.5 ± 14.0***	4461.0 ± 933.6	3822.4 ± 1323.1**
20 cm	51.8 ± 18.3	38.3 ± 16.8***	97.9 ± 20.3	60.8 ± 16.4 ***	6187.9 ± 1730.6	4411.0 ± 1415.8***
25 cm	58.7 ± 17.4	44.6 ± 17.0***	112.2 ± 21.7	68.8 ± 13.9***	7222.2 ± 2250.0	5127.4 ± 1400.3***

*p<0.05; **p<0.01; ***p<0.001 (N/kg)

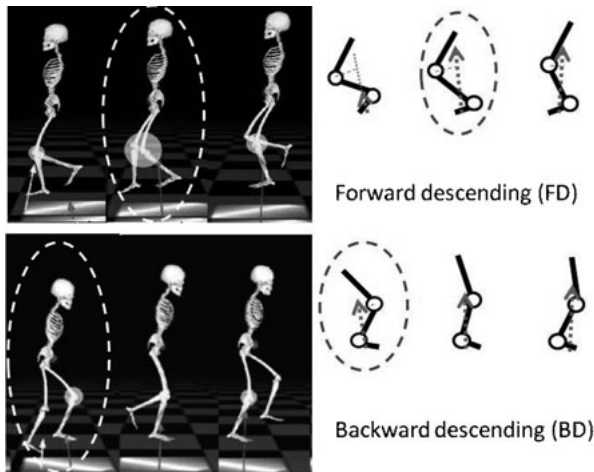


Fig. 2. Relationship between knee joint and floor reaction force.

The dotted-line circle indicates JF2. The dotted-line arrow indicates the floor reaction force vector. The dotted-line indicates the perpendicular distance between the knee position and the floor reaction force vector.

range of motion (mean, 104.3°) for OA patients¹⁵. Hinman et al. also reported poor knee control due to insufficient extension moment and pain in the knee¹⁶. Therefore, when providing motion guidance to OA patients, a descending method with an angle smaller than the passive knee flexion angle must be selected.

In the present study, FD required flexion angles of 65.7°(10 cm) to 101.9°(25 cm), and BD required flexion angles of 43.4°(10 cm) to 73.6°(25 cm). Flexion angles could thus be reduced by 28–34% using BD instead of FD. BD is thus effective in OA patients with a narrow range of controllable knee flexion or restricted knee flexion.

Past studies have found movements with large knee flexion angles, such as squatting and kneeling, generate a large knee extension moment and knee joint force¹⁷. In the present study, knee extension moments M1 and M2 were greater for movements with a large knee flexion angle, showing similar

results to our previous study¹⁰). Knee extension moment in the present study was high, because as knee flexion increased, the center of the knee moved forward to lengthen the distance with the floor reaction force vector (moment arm) to increase the knee extension moment. In addition, the moment arm extended during FD and shortened during BD (Fig. 2). This shows that BD reduces knee extension moment as compared to FD.

Not only floor reaction force, but also movements of periarticular muscles of the knee play a large role in the generation of knee joint force¹⁸). Knee joint force is thus low for BD because of the small knee extension moment. With regard to knee joint force while moving, different values have been reported for walking, deep knee flexion and kneeling^{19–21}). The same applies to knee joint force during stair ascending and descending, and this was due to differences in riser height, subject body type and gender, marker placement and interpolation methods, and joint force extraction methods²²). During FD in the present study, joint force per body weight was 5.8-fold with the 10-cm riser height, 7.8-fold with the 15-cm riser height, 9.8-fold with the 20 cm riser height and 11.4-fold with the 25 cm riser height. Based on the above-mentioned relationship to joint angle and moment, the magnitude correlations were similar. During BD, joint force was 4.0-fold with the 10-cm riser height, 5.1-fold with the 15-cm riser height, 6.1-fold with the 20-cm riser height and 6.9-fold with the 25-cm riser height, thus lowering the knee joint force by 30–40% when compared to FD.

During stair descending, all parameters exhibited biphasic changes: the first phase indicated shock absorption during landing; and the second phase indicated descending control of the center of gravity associated with stair descending.

According to a past study on the relationship between descending speed and floor reaction force, shock during landing increased when descending speed was fast. As a result, the first peak increased. However, the second peak increased when descending speed was slow because descending control was important²³). When OA patients experience difficulty using the knees to control the center of gravity due to insufficient knee extension moment of the supporting leg²⁴), shock during landing is believed to be high. Subsequently, joint stress for the leading leg may increase. Furthermore, all parameters were lower throughout

one-leg standing during BD, and because the sum of joint forces was also lower, knee joint stress on both leading and supporting legs could be reduced throughout stair descending.

In the present study, because the speed of descending was not regulated, the relationship between speed and each parameter could not be compared. However, the first and second peaks of all parameters increased as the riser height increased, suggesting that higher levels of descending control and shock absorption during landing are required. With regard to ΣJF , the degree of decrease was greater for the 25-cm riser height (29.0%) than for the 10-cm riser height (10.4%), suggesting that BD is effective for descending stairs with high step heights.

The likely site of OA onset is the articular surface during 30–60° knee flexion. The reason for this is that these angles are frequently required for ADLs, such as walking²⁵). With knee flexion $\geq 30^\circ$, the contact area of the tibia and femur and the load-bearing area of the meniscus decrease²⁶), and knee flexion increases joint force²⁷), thus increasing pressure/contact area. Excessive loading on the knee destroys joint cartilage and induces microscopic injury, thus inducing pain during movements. OA patients thus need to acquire movements to reduce knee joint force and decrease knee flexion angles. Compared to normal knees, the contact area for artificial knee joints is also smaller, and an increase in joint force causes joint surface polyethylene friction and damage²⁸). Similarly, control of joint force and knee flexion angle is important. The present study verified that there are low joint forces, joint moments and knee flexion angles during BD, suggesting BD as an appropriate compensatory movement for OA patients and patients following artificial knee joint replacement.

However, the present study did not assess actual OA patients, and a study of this population will be necessary in the future. Several subjects also complained of backward instability during BD. Therefore, during BD, safety must be ensured by instructing subjects to lean the body forward while using a handrail.

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