Percentage Contribution of Lower Limb Moments to Vertical Ground Reaction Force in Normal Gait

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ABSTRACT

Objective: The purpose of this study was to investigate how the hip, knee, and ankle moments in the sagittal plane contribute to the vertical ground reaction force (GRF) in healthy participants during normal speed of walking.

Methods: Forty healthy male individuals volunteered to participate in this study. They were filmed using 6 high-speed (120 Hz) Pro-Reflex infrared cameras (Qualisys) while walking on an Advanced Mechanical Technology Incorporation force platform. The data collected were the percentage contribution of the moments of the hip, knee, and ankle joints in the sagittal plane at the instant of occurrence of the first peak, second peak, and trough of the vertical GRF.

Results: The results revealed that at the first peak of the GRF (loading response), the highest contribution was generated from the knee extension moment followed by the hip extension moment. Knee flexion and ankle plantar flexion moments produced a high contribution to the trough of the GRF (midstance) with approximately equal values. The second peak of the GRF was mainly produced by the ankle plantar flexion moment.

Conclusion: The role of hip extension moment is secondary to knee extension moment in the first peak of GRF. Knee flexion moment is secondary to ankle plantar flexion moment in the second peak of GRF. Both knee flexion and ankle plantar flexion moments have equal contribution during midstance. (J Chiropr Med 2019;18:90-96)

Key Indexing Terms: *Gait Analysis; Muscle Strength; Lower Extremity*

INTRODUCTION

The stance phase of gait is the supporting phase that represents 60% of the gait cycle. It is subdivided into double-limb stance and single-limb stance subphases. In double-limb stance, both feet make contact with the ground, but in single-limb stance only 1 foot contacts the ground. The muscles that are active during the stance phase act to prevent buckling of the supporting limb. These muscles include the tibialis anterior, the quadriceps, the hamstrings, the hip abductors, the gluteus maximus, and the erector spinae.¹ Forces generated by muscles

are transferred from one segment to the other, causing each foot to apply a force to the ground. Then, the ground responds by applying ground reaction force (GRF) to each foot. These forces are equal in magnitude and opposite in direction.²

During the gait cycle, the body's center of mass drops onto and moves across the supporting foot. That results in the generation of vertical, anterior-posterior, and medial-lateral GRF. In a normal gait cycle, the vertical GRF has 2 peaks and a valley.³ During loading response and terminal stance, the vertical GRF is slightly higher than the body weight, but during midstance, the GRF is slightly lower than the body weight, showing a valley between the 2 peaks.⁴ Internal joint moments are commonly used in gait analysis to identify the role of each internal force in supporting the body over the stance limb. Several researchers used dynamic analysis to quantify the contributions of joint moments in supporting and maintaining the balance of the body during its translation at the different phases of the gait cycle.⁵

The term *support moment* is defined as the sum of the ankle plantar flexion, knee extension, and hip extension moments. The support moment reflects a consistent total limb pattern that supports the body against the ground and is significantly correlated with the vertical GRF. The GRF is considered equivalent to the acceleration of the center of mass of the

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human body⁶ because $F = M A$, where M is the mass and A is the acceleration. Acceleration during walking is the product of the sum of the constant gravitational acceleration (g) and the acceleration of center of gravity (a). If the contribution of each joint's moments of the lower limb to the vertical GRF was accurately detected, it might be possible to determine which muscle group should be strengthened to improve various gait abnormalities and to apply this on patients experiencing gait dysfunctions. No previous study investigated the percentage contribution of joint moments to the GRF using a 3-dimensional (3D) motion-tracking system. Therefore, the purpose of this study was to quantify the percentage contribution of hip, knee, and ankle moments in the sagittal plane to the vertical GRF in healthy individuals during normal speed of walking.

METHODS

Participants

Forty healthy male individuals volunteered to participate in this study. Their mean $\pm$ (standard deviation) age, body mass, and height were $24.2 \pm (2.54)$ years, $62.25 \pm (4.52)$ kg, and $160.5 \pm (3.25)$ cm, respectively. Only participants with no mechanical or musculoskeletal disorders were included in the study. The Research Ethics Committee of Faculty of Physical Therapy of Cairo University approved this study. The registry number for this study is P.T. REC/012/001582.

Procedures

The Qualisys 3D gait analysis system was used to record the kinetic gait parameters for each individual. The system consisted of 6 high-speed infrared ProReflex cameras with a frame rate of 120 Hz interfaced with an Advanced

Mechanical Technology Incorporation (AMTI) force platform (Fig 1A). The Q track software was used to capture the walking individual. Each lower-limb joint position was picked up by the cameras to detect the relative body segments during motion. These were detected using 20 passive reflective markers placed on specific sites on the body as determined and described by the ProReflex user manual (Fig 1B). All markers were attached to the skin via double-sided adhesive tape.⁷

Before capturing the walking parameters, the system was calibrated to enable each of the 6 cameras to pick up the positions of the reflective markers in the trajectory field of the walkway.⁷ Each individual was instructed to walk as naturally as possible. The placement of the foot on the force platform was observed so that the entire foot was placed on the platform. The data were collected from 3 walking trials and averaged.

The trace of the vertical GRF during the stance phase in normal walking shows a curve constituting 2 peaks and a valley in between (Fig 2). The first peak develops at the instant of loading response. The valley occurs in the midstance period. The second peak develops at the time of heel off (onset of forward propulsion). The measuring unit of the GRF was in Newton and was then expressed as percentage relative to the body weight (% body weight). The following kinetic parameters were collected: (1) maximum hip flexion and extension moments; (2) maximum knee flexion and extension moments; (3) maximum ankle plantar flexion and dorsiflexion moments during gait cycle; and (4) hip, knee, and ankle moments at the GRF peaks and valley. The moment was calculated relative to the body weight (in Nm/kg). For the statistical analysis, the moment is converted into percentage relative to the maximum magnitude of the moment generated during the gait cycle. The percentage contribution of each joint moment was calculated by dividing the moment created at

Fig 1. Laboratory setup. (A) ProReflex cameras and the walkway having the force platform in the middle. (B) Passive reflective markers placement.

Fig 2. Trace of the vertical GRF (blue) during normal gait cycle. Red is the anteroposterior GRF and green is the mediolateral GRF. GRF, ground reaction force.

Table 1. Percentage Contribution of Lower-Limb Sagittal Moments (Expressed in Percentage % From the Maximum Moment [Nm/kg] Created During Stance)

Ground Reaction Forces (Expressed in N)	Hip Moments		Knee Moments		Ankle Moments	
	Flexion	Extension	Flexion	Extension	Plantar flexion	Dorsiflexion
First peak	27.22	36.81	13.71	80.2	16	0
Valley	30.08	34.75	53.88	17.6	54.1	0
Second peak	36.9	11.95	41.33	15.9	99.1	0

any of the 3 intervals of the GRF by the maximum moment generated during whole gait cycle. For example, the percentage contribution of hip flexion moment to the first peak of GRF is calculated as follows: % contribution of hip flexion moment to the first peak of GRF = hip flexion moment at first peak (Nm/kg) / maximum moment generated from hip joint during the gait cycle.

RESULTS

The results (Table 1 and Fig 3) indicated that in the first peak of GRF, the contribution of knee extension moment was the greatest. The second contribution was produced from the hip extension moment followed by hip flexion moment. Knee flexion moments and ankle plantar flexion

Fig 3. Percentage contribution of lower-limb moments to vertical GRF during stance phase of gait. The black curved line shows how the contribution preserves the classical shape of the GRF. GRF, ground reaction force.

Fig 4. (A) The hip joint flexion (downward) and extension (upward) moments during gait. (B) The knee joint flexion (downward) and extension (upward) moments. (C) The ankle joint dorsiflexion (downward) and plantar flexion (upward) moments.

produced approximately equal contributions in this phase (13% and 16%, respectively). In the valley of GRF curve, the ankle plantar flexion moment (54.1%) and knee flexion moment (53.88%) produced nearly equal contribution to this interval. The second peak of GRF was produced by ankle plantar flexion moments, in which they produced 99.1% of their maximum moment generated during stance followed by knee flexion and hip flexion. The least contribution in this peak was reported from knee extension (15.9%) and hip extension (11.9%) moments. The ankle dorsiflexion moment was reported to have no role in the intervals of the GRF. Figures 4A, B, and C represent the hip, knee, and ankle moments, respectively, during stance.

DISCUSSION

This study focuses on the contributions of lower-limb moments to the vertical GRF response. To the authors' knowledge, no previous study was conducted to arrange the sequence of percentage contribution of each sagittal plane joint moment during the supporting phase of normal walking using 3D gait analysis. The results indicated that the pattern that appeared in the vertical GRF is the responsibility of the lower-limb joint moments with a varying contribution. At the first GRF peak, the highest contribution was generated from the knee extension moment (80.2%) followed by hip extension (36.8%), then hip flexion (27.2%), plantar flexion (16%), and lastly knee flexion (13.7%). At the GRF valley, knee flexion (53.88%) and ankle plantar flexion (54.1%) produced equal contributions followed by hip extension (43.75%) and flexion (30.08%) moments. The least contribution to the valley was from knee extension (17.6%). In the second GRF peak, the maximum contribution was reported from the ankle plantar flexion (99.1%) moment. Knee flexion (41.33%) and hip flexion (36.9%) moments came in the second level of contribution. The least contribution comes from hip extension (11.95%) and knee extension (15.9%).

The body's center of mass (COM) acceleration fluctuates during walking. At loading response, the body's COM is moving downward, generating the first peak of GRF curve. During the valley, the need is for controlling the upward acceleration of the COM and the forward advancement of the trunk.³ This trunk advancement should be controlled by activities of the plantar flexors and knee flexors to control the advancement of the tibia and knee flexors, which control the advancement of the femur. Finally, in the second GRF peak, which corresponds to the terminal stance phase, the ankle plantar flexors should control the downward acceleration of the COM.

The reason for the obtained arrangement of moment contributions to the vertical GRF can be attributed to the line of action of the GRF relative to the joint. This line was defined as ground reaction force vector (GRFV). At the first

GRF peak, the GRFV is located behind the ankle and knee but anterior to the hip. This vector creates an external torque, which is resisted by internal joint torque created mainly by surrounding musculature.³ In the early stance, in the sagittal plane, the hip musculature generates torque that serves to accept the body weight, control the trunk, and extend the hip, whereas in the second half of the stance phase, hip flexors and the anterior joint capsule generate the hip flexion moment to decelerate extension. The same explanation was reported by Pandy,⁸ who indicated that both hip extensors and hip abductor muscles contribute significantly to vertical motion of the COM and therefore to the appearance of the first peak in the vertical GRF in early single-limb stance.

At the knee joint, the moment pattern during the loading response was created by eccentric contraction of the quadriceps muscle. During midstance, the extensor moment of the knee joint decreases, and the moment usually changes into a flexor dominant moment for the end part of stance.^{9,10} The equal contribution from both knee flexion and ankle plantar flexion moment can be attributed to the alignment of the lower limb at which the body weight is supported over the reference extremity. The pathway of GRFV anterior to the knee and ankle joints at this interval creates knee extension and ankle dorsiflexion moments that should be counterbalanced by knee flexion and ankle plantar flexion moments. They produced an equal contribution because the ankle muscles have attachments near the knee joint.

The second peak of the GRF was mainly produced by the ankle plantar flexor moment (99.1%) followed by knee and hip flexor moments, and the least contribution was from knee and hip extensors. The ankle plantar flexion moment prevails throughout the rest of the stance phase after the short role of dorsiflexors at heel contact. This plantar flexion moment eccentrically controls the tibial advancement over the foot and plantar flexes the ankle joint at push-off, providing good propulsion.⁹

In the same context, modeling and simulation studies have supported the findings of the current study, showing that the body support during normal speed of walking is provided by the hip and knee extensors in early stance, and the ankle plantar flexors are the primary contributors in late stance.^{5,11} In addition, Fukui et al¹² examined the mutual relationship among kinetic variables of the hip, knee, and ankle joints during different phases of gait, and their findings supported the current study results. They revealed that the hip extension moment at initial contact, knee extension moment at loading response, ankle plantar flexion and knee extension moments at midstance, and ankle plantar flexion moment from terminal stance to pre-swing had a relatively high correlation to the vertical GRF.

Ankle plantar flexors have been shown to be important contributors to support, forward propulsion, and swing initiation during normal walking.^{11,13} The gastrocnemius

and soleus play a crucial role, as ankle plantar flexors, in the stance phase of gait in both healthy individuals and those with gait abnormalities. Both muscles are active from midstance through the beginning of pre-swing in normal walking,¹⁴ generating plantar flexion moments around the ankle. Some studies attribute a larger forward propulsion role to soleus,¹⁵ whereas others suggest the gastrocnemius plays the larger role.¹³ Some of the differences between studies may be due to the strong dependence of muscle function predictions on musculoskeletal geometry and ground contact model assumptions.^{16,17} It was previously suggested that ankle plantar flexors provide the active push-off during the late part of the stance phase owing to the leverage put forth by the body alignment with respect to GRFV.¹⁸

Anderson and Pandy⁵ reported contradicting results concerning the ankle joint muscular contribution to vertical GRF. They illustrated that muscles do most of their work in accelerating the body's COM, and so the support of the COM is brought about by few major muscle groups such as ankle dorsiflexors, hip and knee extensors, and hip abductors. However, the authors did not specify the contribution of these muscle groups. The contradiction between their study and the current study may be due to the method of data collection as indicated by the authors themselves. They showed that their findings may be limited because the GRF is predicted by the model, which is different from force platform measurements obtained from healthy individuals.

Moreover, the minimal contribution from hip extension moment in the second peak of the GRF in the current study compared with ankle plantar flexors may be attributed to the tradeoff between the ankle and the hip joints during walking. Simple increases in ankle push-off can substantially decrease hip muscle moments and powers during human walking.¹⁹ The findings of this study are important in the clinical setting. Clinicians need to know which groups of muscles contribute more in different phases of the gait cycle. Not only the group importance, but also its percentage contribution in the stance phase of gait. For example, by knowing that the plantar flexors produced 99% of their activity during pre-swing followed by activity of knee flexors, if a patient has a musculoskeletal disorder affecting the plantar flexor muscles, the clinician should focus on knee flexor strengthening exercises to compensate for this disability and to enhance fast recovery of the patient's weak plantar flexors, that is, one muscle group can be used to enhance recovery of the other disabled muscle group.

Limitations

The study was limited by the inability to generalize the findings beyond the investigated age group. The inability to specify each individual muscle torque contribution was another limitation, which may cause the findings to contradict with other studies investigating individual muscle electromyogram recording. Only sagittal plane moment contribution

was calculated while the GRF has its 3D moment values around the joints. These moment contributions (frontal and transverse) may be considered in future studies.

CONCLUSION

The maintenance of stance limb stability and a normal pattern of GRFV during the normal speed of walking requires an interplay of joint moments with varying percentages. This pattern provides information relevant for clinical settings. Weakness in a group of muscles contributing to joint moments can be compensated for by increasing the activation of another group.

FUNDING SOURCES AND CONFLICTS OF INTEREST

No funding sources or conflicts of interest were reported for this study.

CONTRIBUTORSHIP INFORMATION

Concept development (provided idea for the research): S.M.E., G.M.E.

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Practical Applications

- Patients with gait disturbances may have muscle group dysfunctions.
- Muscle groups work in harmony to obtain normal pattern of GRF. Weakness of one muscle group can be regained by increasing strength of other muscle group to reach the normal pattern and speed of gait.

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