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Original article

Gait analysis using three-dimensional motion and ground reaction force systems in patients with hemiplegia treated with botulinum toxin type A in ankle plantar flexors

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Abstract

Objective: The efficacy of botulinum toxin type A (BoNT-A) injection on spasticity has usually been measured using the range of motion (ROM) of joints and Modified Ashworth Scale (MAS); however, they only evaluate muscle tone at rest. We objectively analyzed the gait of three patients with hemiplegia using three-dimensional motion analysis and ground reaction force (GRF) systems to evaluate muscle tone during gait.

Materials and Methods: We measured passive ankle dorsiflexion ROM with knee extension and the MAS score for clinical evaluation, and gait speed, stride length, single-leg support phase during the gait cycle, joint angle, joint moment, and GRFs for kinematic evaluation before and one month after BoNT-A injection.

Results: All patients showed an increase in ankle dorsiflexion ROM, improvement in MAS score, and increase in stride length. Case 1 showed an increase in gait speed, prolongation of the single-leg support phase, increase in hip extension angle and moment, and improvement in the vertical and anterior-posterior components of the GRFs. Case 2 showed an increase in gait speed, improvement in double knee action, increase in ankle plantar flexion moment, and improvement in propulsion in the progressive component of the GRFs. Case 3 exhibited a laterally directed force in the GRFs.

Conclusion: We evaluated the effects of BoNT-A injections in three patients with hemiplegia using three-dimensional motion analysis and GRFs. The results of the gait analysis clarified the improvements and problems in hemiplegic gait and enabled objective explanations for patients.

Key words: botulinum toxin type A, gait analysis, three-dimensional motion analysis, ground reaction forces, spasticity

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Introduction

Many patients suffer from hemiplegia caused by cerebrovascular disorders, and many of them have presented with gait disturbances due to lower limb spasticity. Improving walking ability by reducing lower limb spasticity is one of the most important goals of rehabilitation for patients with hemiplegia. Over the last decade, botulinum toxin type A (BoNT-A) therapy for lower limb spasticity caused by cerebrovascular disorders has been used to improve walking ability. Although the range of motion (ROM) of joints and Modified Ashworth Scale (MAS) are often used for post-injection evaluation[1], these evaluations, which are performed at rest, cannot fully evaluate muscle tone during gait. It requires a means of evaluating muscle tone during gait because muscle tone generally increases during gait rather than at rest. We considered that the angles and moments of each joint evaluated using three-dimensional motion analysis, and ground reaction forces (GRFs) could be used to assess muscle tone during gait. In actual clinical practice, gait analysis by observation is widely used to evaluate gait disturbance; however, it depends on the ability and experience of the observers. Gait analysis using three-dimensional mo-

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tion analysis and GRF systems can capture detailed changes in gait that cannot be detected by observation and enable a more objective and reliable evaluation. Objective evaluation of gait provides appropriate advice for gait improvement, regardless of the ability and experience of the observers. However, to our knowledge, there are few reports on the objective evaluation of gait using three-dimensional motion analysis and GRFs in patients with hemiplegia treated with BoNT-A therapy in the past literature. This study aimed to evaluate the effects of BoNT-A injections in three patients with hemiplegia using three-dimensional motion analysis system and GRF systems.

Patients and Methods

This retrospective study was conducted at our hospital between 2018–2022. The participants were three hemiplegic patients with lower limb spasticity. A three-dimensional motion analysis system (Locus 3D MA 3000, Anima Corp., Tokyo, Japan) with 10 infrared cameras was used to capture and analyze the motion with a sampling frequency of 100 Hz. Four force plates (MG-1060, Anima Corp.) in synchrony with the cameras were used to capture the GRFs and identify heel-contact and toe-off of the stance phase with a sampling frequency of 100 Hz. Gait analysis was performed using a computerized gait system (Anima Corp.) to measure kinematic data (gait speed, stride length, single-leg support phase, hip, knee, and ankle joints angles and moments, and GRFs) during gait. The participants were instrumented with passive reflective markers for gait analysis and asked to walk at a comfortable speed along a 6-m walkway. Twelve reflective markers were placed on the acromion, anterior-superior iliac spine, great trochanter, lateral knee joint axis, lateral malleolus, and fifth metatarsal head. BoNT-A was injected under ultrasonography guidance and electrical stimulation. We measured passive ankle dorsiflexion ROM with knee extension and MAS score as a clinical evaluation, and measured gait speed, single-leg support phase of the affected limb during the gait cycle, joint angle, joint moment, and GRFs as a kinematic evaluation before and at one month after injection. Gait was analyzed in all the three patients without the use of aids or braces. In the GRF graphs, the horizontal axis represents time, which is normalized by setting one gait cycle at 100%. In the graph of the joint angles and moments, the horizontal axis represents the time normalized to 100% of one gait cycle starting from the heel contact point.

Results

Case 1

A 45-year-old man with gait disturbance due to spasticity of the right lower limb (Br.stage lower limb 3) after cerebral hemorrhage was treated with BoNT-A injections. A total of 300 units of BoNT-A were injected into the gastrocnemius, tibialis posterior, flexor digitorum longus, and flexor hallucis longus muscles. After the injection, it showed improvement in ROM in ankle dorsiflexion from 0° to 5° and a decrease in MAS score from 2 to 1+ as a clinical evaluation, and an increase in gait speed, increase in stride length, prolongation of single-leg support phase of the affected limb, increase in maximal hip extension angle in the stance phase, increase in hip extension moment in the load response phase, early rise of the vertical component of GRFs, and an improvement in the anterior-posterior component of the GRFs as a kinematic evaluation (Table 1 and Figure 1).

Case 2

A 30-year-old man with gait disturbance due to spasticity of the right lower limb (Br.stage lower limb 3) after a left cerebral hemorrhage was treated with BoNT-A injection. A total of 200 units of BoNT-A were injected into the gastrocnemius muscle. After the injection, it showed improvement in the ROM in ankle dorsiflexion from –5° to 0° and a decrease of MAS score from 3 to 2 as a clinical evaluation, and an increase in gait speed, increase in stride length, improvement in double knee action, increase in ankle plantar flexion moment in the late stance phase, and improvement in propulsion in the progressive component of GRFs as a kinematic evaluation (Table 1 and Figure 2).

Case 3

A 19-year-old man with gait disturbance due to spasticity of the left lower limb (Br.stage lower limb 4) after a right cerebral infarction was treated with BoNT-A injection. A total of 100 units of BoNT-A were injected into the gastrocnemius muscle. After the injection, it showed an increase in ROM in ankle dorsiflexion from −5° to 0° and improvement in MAS score from 3 to 2 as a clinical evaluation and lateral-directed force in GRFs in the load response phase as a kinematic evaluation. The gait speed did not increase; however, an increase in stride length was observed. No significant changes were observed in either joint angle or moment (Table 1 and Figure 3).

Discussion

In this study, we performed gait analysis of three patients with hemiplegia using three-dimensional motion analysis and GRFs before and at one month after BoNT-A injection. All the patients showed an increase in ROM in ankle dorsiflexion, improvement in MAS score, and increase in stride length. In addition to the common changes observed in all the patients, certain changes were also observed in each patient. Case 1 showed an increase in gait speed, prolongation of the single-leg support phase of the affected limb, increase

Table 1 Summarized outcomes observed at pre- and post-injection

	Case 1		Case 2		Case 3	
BoNT-A injection muscles	m.gastrocnemius m.tibialis posterior m.flexor digitorum longus m.flexor hallucis longus		m.gastrocnemius		m.gastrocnemius	
	Pre-injection	Post-injection	Pre-injection	Post-injection	Pre-injection	Post-injection
ROM in ankle dorsiflexion (degree)	0	5	−5	0	−5	0
MAS	2	1+	3	2	3	2
Gait speed (m/sec)	0.32	0.33	0.58	0.79	0.70	0.62
Stride length (m)	0.53	0.55	0.80	1.05	0.78	0.79
Single leg support phase (%)	17.4	32.3	37.4	32.5	31.0	28.2

BoNT-A: botulinum toxin type A; ROM: range of motion; MAS: modified Ashworth scale.

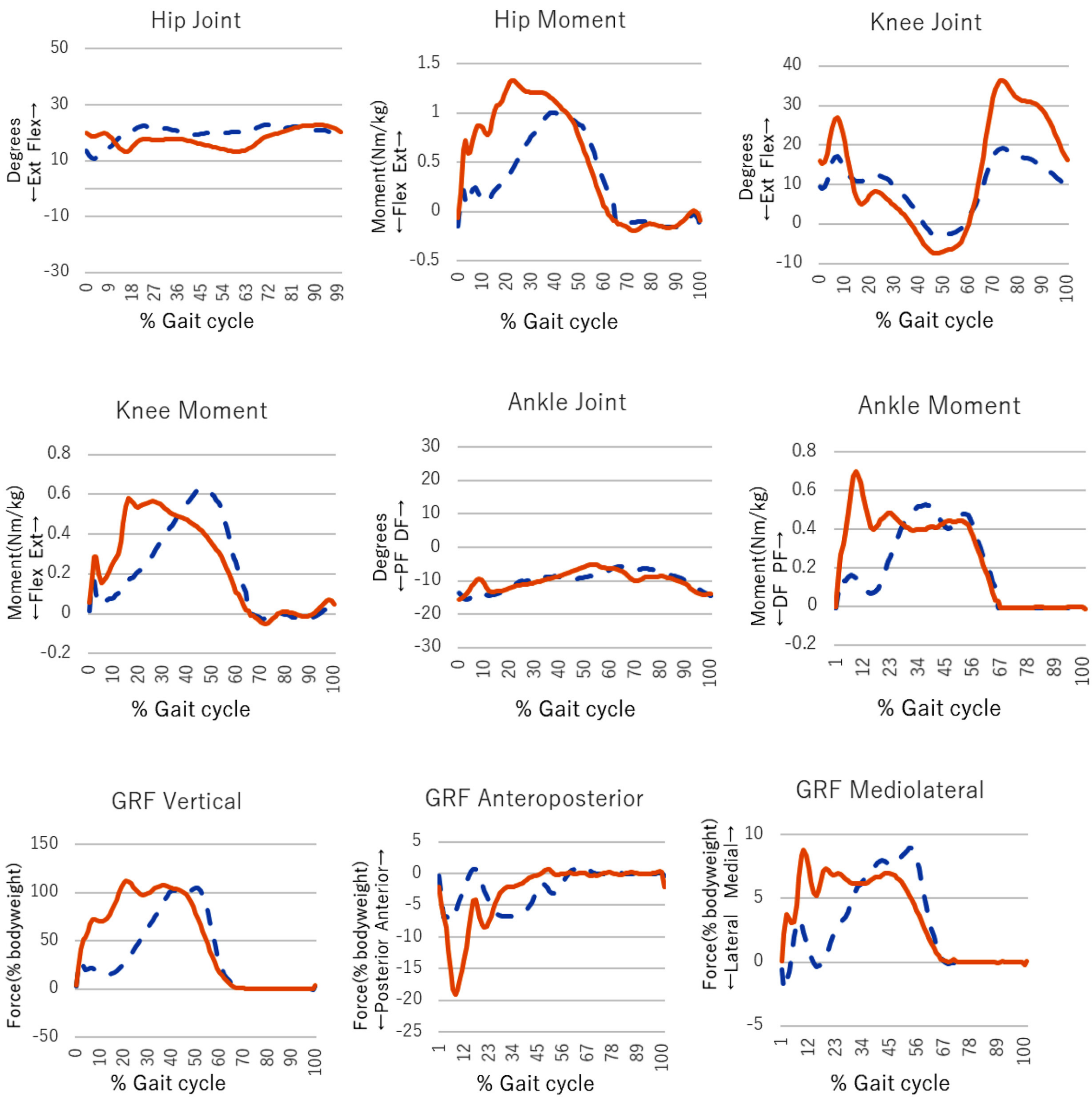

Figure 1 Changes in joint angles, joint moments, and ground reaction forces (GRFs) during gait in case 1.
The dotted line shows the results of pre-injection and the solid line shows the results of post-injection.

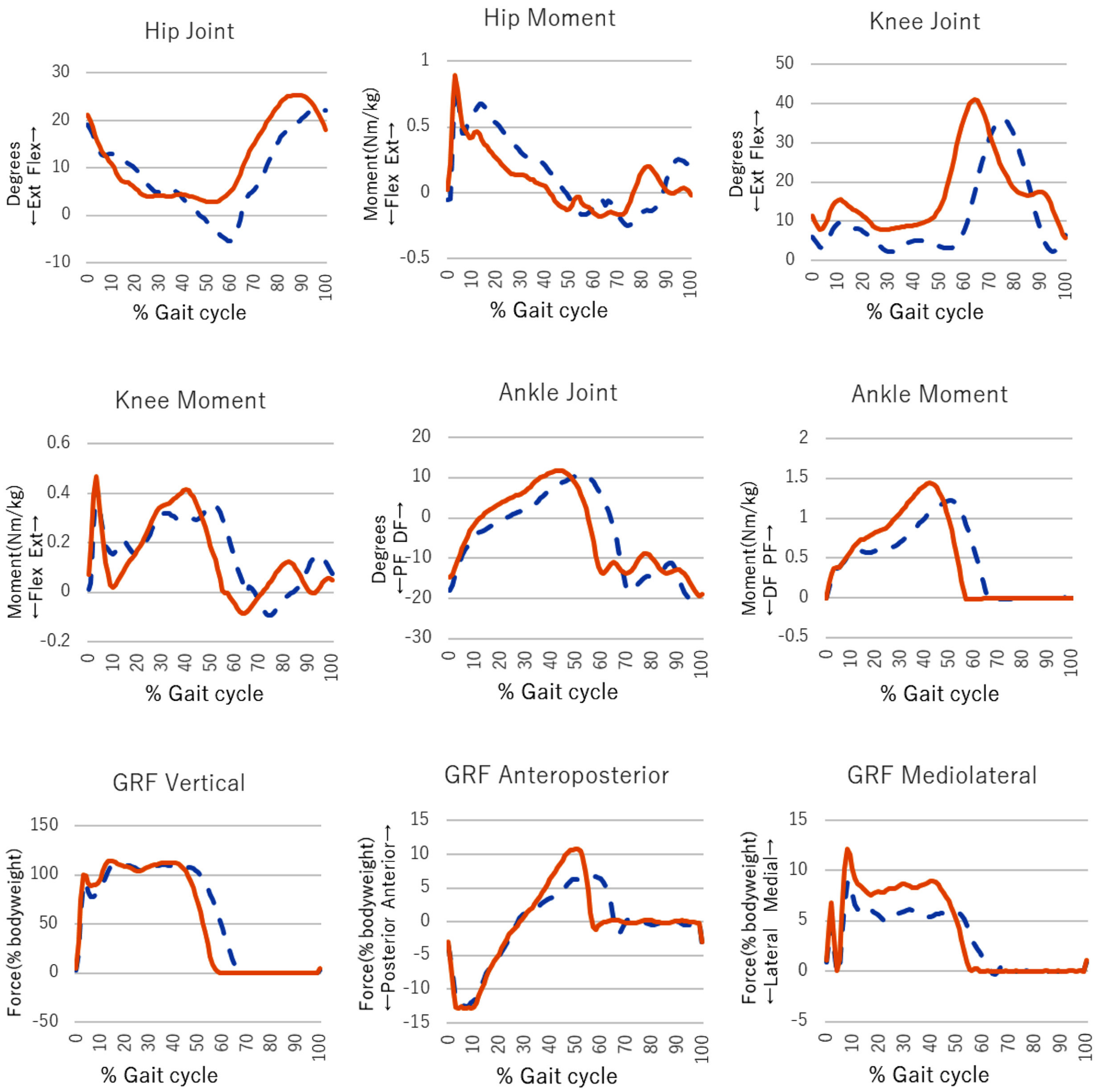

Figure 2 Changes in joint angles, joint moments, and ground reaction forces (GRFs) during gait in case 2.
The dotted line shows the results of pre-injection and the solid line shows the results of post-injection.

in the maximal hip extension angle in the stance phase, increase in the hip extension moment in the load response phase, early rise in the vertical component of the GRFs, and improvement in the anterior-posterior component of the GRFs. Case 2 showed an increase in gait speed, improvement in double knee action, increase in ankle plantar flexion moment in the late stance phase, and improvement in propulsion in the progressive component of the GRFs. Case 3 exhibited a laterally directed force in GRFs during the load response (Figure 4).

Previous studies have shown that the hip extension and ankle dorsiflexion moments in the early stance phase and ankle plantar flexion and hip flexion moments in the late stance phase are correlated with gait speed. These forces control the center of gravity, and their lack causes gait disturbances in patients with hemiplegia[2]. For case 1, the improvement in ankle joint ROM due to a decrease in the triceps surae muscle spasticity enabled heel contact, and it formed a driving force to move the center of gravity forward and upward, leading to an increase in the maximal hip extension angle and increase in hip extension moment in the early stance phase. This contributes to an increase in gait speed. Additionally, increased ankle dorsiflexion and hip extension angles were reported to contribute to an increase in the propulsive force of the gait[3]. Thus, the increase in the hip extension angle in case 1 led to a better gait. In case 2, the improvement in ankle joint ROM caused heel rocker and ankle joint rocker function in the early phase of stance,

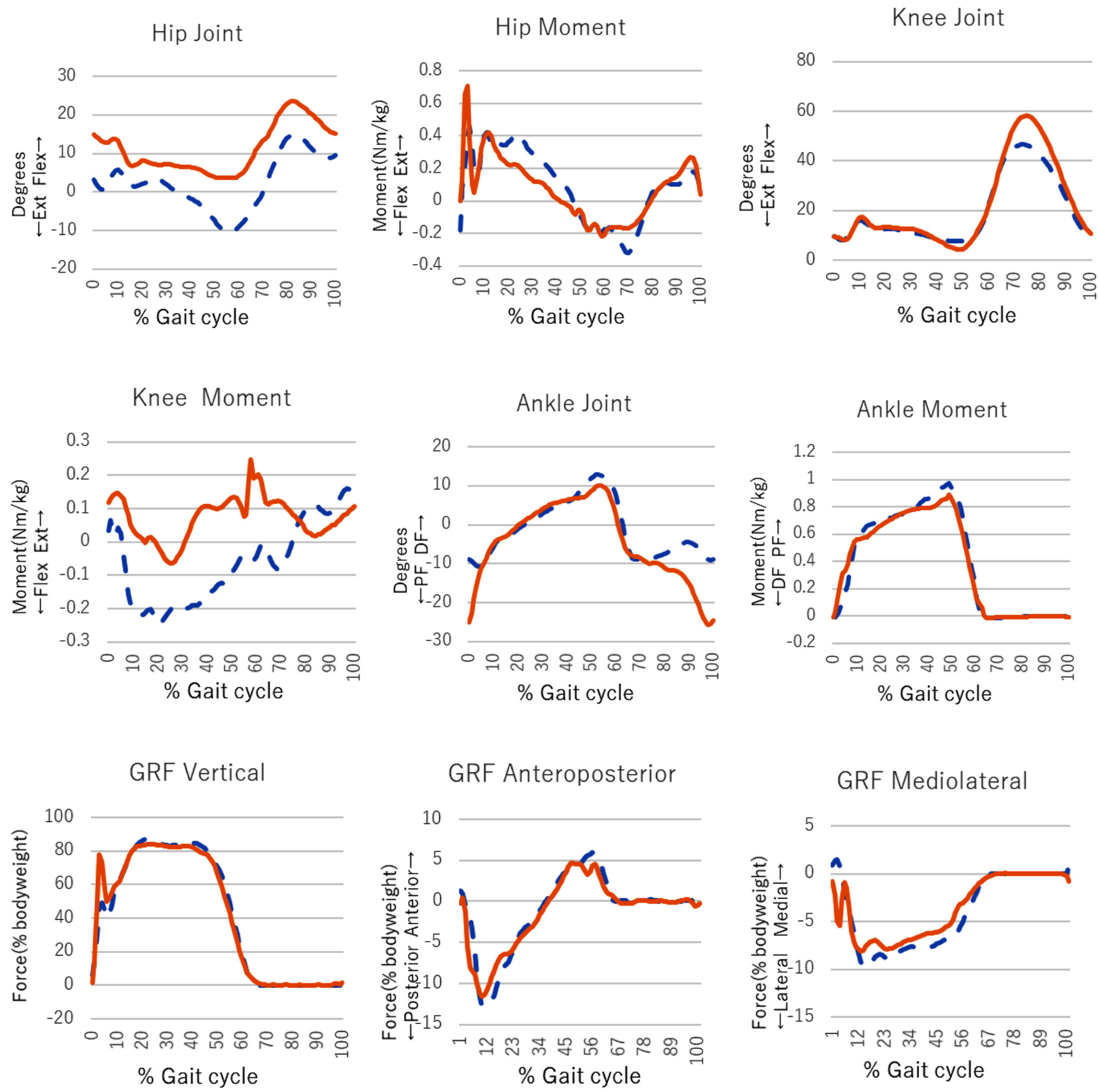

Figure 3 Changes in joint angles, joint moments, and ground reaction forces (GRFs) during gait in case 3. The dotted line shows the results of pre-injection and the solid line shows the results of post-injection.

and the center of gravity shifted forward and upward. It also showed an increase in ankle plantar flexion moment during the late stance phase. This led to improved double knee action and increased gait speed. In case 3, the gait speed decreased, but only the stride length increased. Hemiplegic gait is characterized by short stride length, especially the step length from the paralyzed side to the non-paralyzed side[4]. Gait asymmetry was improved by spasticity reduction, and the stride length increased in all the three cases. However, the gait in case 3 did not change kinematically after BoNT-A injection, as much as in the other cases. The dosage may have been insufficient because the patient received BoNT-A therapy for the first time. Additionally, because he had a high walking ability, his gait did not show much change.

As for the GRFs, the early rise of the vertical component in the GRFs, as shown in case 1, suggests an early increase in overload of the affected lower limb. This led to an increase in all joint moments in case 1. The improvement in the anterior-posterior component of the braking force and propulsive force, which cases 1 and 2 showed, seemed to result from heel contact and a smooth shift in the center of gravity. The improvement in propulsive force could be due to the increase in gait speed; however, the smooth shift in the center of gravity might have caused a forefoot rocker function and generated a propulsive force by decreasing spasticity. Case 3 exhibits a laterally directed force during the load response phase. This was because the improvement

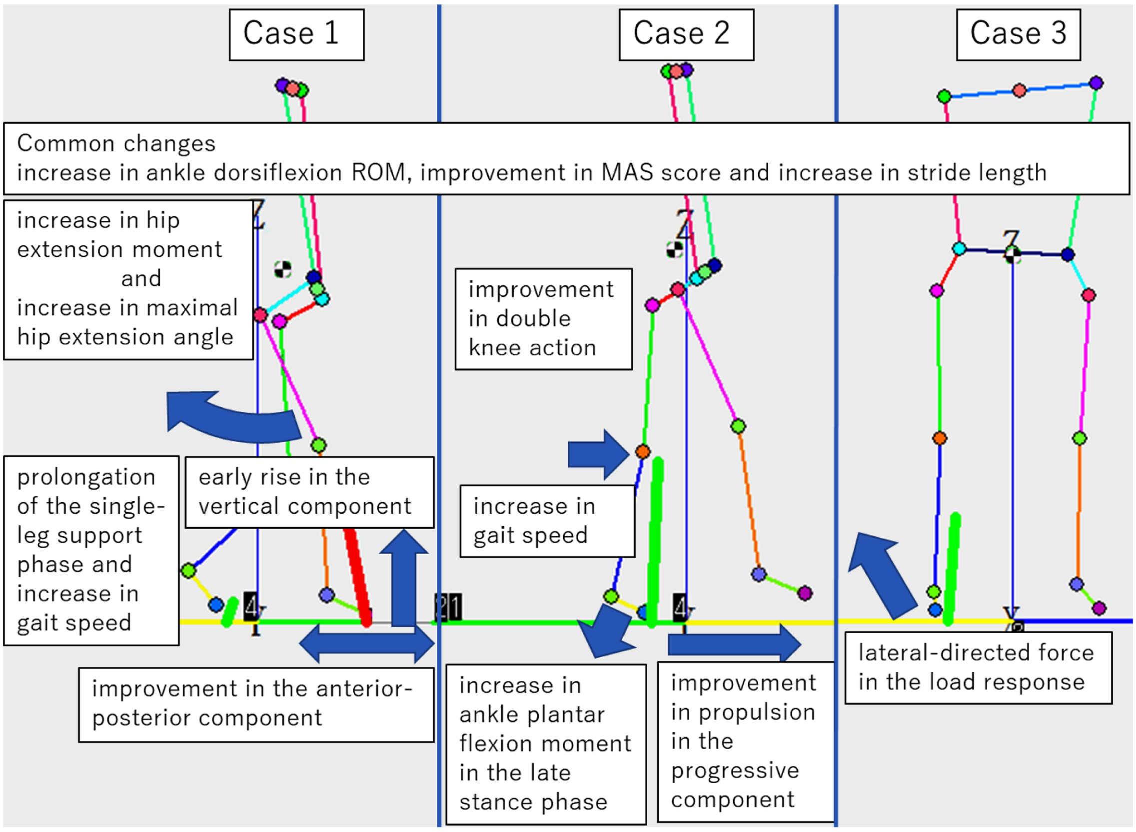

Figure 4 Clinical and kinematic changes in each patient.
ROM: range of motion; MAS: modified Ashworth scale.

in ankle joint ROM resulted in improved heel and ankle rocker functions.

In the present cases, there were no common kinematic changes except for an increase in stride length before and after the BoNT-A therapy. This may be because each patient with hemiplegia has a different gait pattern. Some patients walked with their knees hyperextended during the stance phase, while other walked with their knees mildly flexed during the stance phase. This leads to each patient showing different joint motions. Thus, changing the joint focus sites according to the patient's gait is required.

In a report evaluating GRFs after BoNT-A therapy, the propulsive force was weaker at four weeks after the BoNT-A injection than that at one week because of decreased triceps surae muscle spasticity[5]. This suggests that increasing the dose more than necessary is likely to lead to a decrease in gait speed. This requires a method for determining the appropriate dose, such as objective observation. Thus, the appropriate dose and injection site should be determined based on the gait of each patient. In this regard, objective evaluations, such as three-dimensional motion analysis and GRFs, are useful.

In this study, we evaluated gait more objectively by combining three-dimensional motion analysis and GRFs. Evaluating GRFs can reveal the propulsive force of gait in more detail. Evaluating each joint angle and moment using three-dimensional motion analysis can allow patients with hemiplegia to achieve better gait and not just gait speed. Therefore, further gait improvement can be expected by determining the appropriate dosage and injection sites based on the results of the combined gait analysis.

In clinical practice, many findings can be obtained using gait analysis by observation; however, it is difficult to explain these findings appropriately to patients. As the gait of patients with hemiplegia is valuable and changes with time, an objective means of assessing and explaining the gait is needed. We often show three-dimensional movies of actual walking to patients to explain their gait qualitatively and quantitatively. Patients can easily understand the problems with their gait, which will lead to high-quality rehabilitation.

The study has limitations. First, the sample size was small. Second, the amount of rehabilitation performed during the study period was not standardized. Third, this was a retrospective observational study that used medical records without a control group. Fourth, the participants were males and relatively young. Furthermore, although determining the appropriate dosage and injection sites based on the results of combined gait analysis indicates an improvement in gait, appropriate dosage and injection sites are uncertain, which is a topic for future studies. In the future, we would like to examine more cases and consider the appropriate dosage and injection sites according to gait.

Conclusion

We evaluated the effects of BoNT-A injection in three patients with hemiplegia using three-dimensional motion analysis and GRF systems. The results of the gait analysis clarified the improvements and problems in hemiplegic gait and enabled objective explanations for patients.

Conflict of interest: We have no conflicts of interest to disclose for this paper.

Ethical approval and consent to participate: The purpose and content of this report were explained to the patients in writing, and their consent was obtained after they were informed that their privacy would be respected.

Data availability statements: Data supporting the findings of this study are available from the corresponding author upon request.

Author contributions: MM conceived the study and drafted the original manuscript. MM and TO were responsible for data acquisition and analysis. TO supervised the project. MM wrote the manuscript with the support of TO. All the authors discussed the results and commented on the manuscript. MM and TO revised and edited the manuscript. All authors approved the final manuscript before submission.

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