



## Full length article

# Accuracy evaluation of a method to partition ground reaction force and center of pressure in cane-assisted gait using an instrumented cane with a triaxial force sensor



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## ABSTRACT

Clarifying the biomechanics of cane-assisted gait in elderly individuals and patients with gait disorders is important for developing better therapeutic interventions in the fields of rehabilitation and orthopedics. However, if the foot and the cane in the ipsilateral hand are placed on the same force plate simultaneously, the force plate cannot separate the forces as it records the sum of the forces. To overcome this indeterminacy problem of the ground reaction force (GRF) and the center of pressure (COP) in cane-assisted gait analysis, a method to partition the GRF and COP using an instrumented cane with a force transducer has been proposed. However, the accuracy and precision of the estimated GRF and COP has not been evaluated previously. We therefore reestablished a framework to partition the foot and cane forces during walking using an instrumented cane with a triaxial force sensor and evaluated the accuracy and precision of the method using a force plate array. Cane-assisted gait of healthy adults and hemiplegic patients were measured. Mean accuracy and precision associated with the GRF and COP measurements were approximately  $0.4 \pm 1.4$  N and  $0.2 \pm 2.7$  mm, respectively, indicating that the separations of the GRF and COP were sufficiently accurate for kinetic gait analysis. Although some methodological limitations certainly apply, this system will serve as a useful tool for improved therapeutic interventions.

## 1. Introduction

Gait assistive devices, such as a cane, are often prescribed to improve balance in walking gait for elderly individuals [1–3] and hemiplegic patients [4–7], as well as to reduce loading (force and moment) of the lower limb for patients with gait disorders such as knee osteoarthritis [8–10] and total knee or hip replacement patients [11]. Therefore, efforts have been made to analyze the effect of the use of a cane on the mechanics of walking gait towards establishing more effective interventions as well as safety instructions for using a cane for elderly individuals and patients with gait disorders [12].

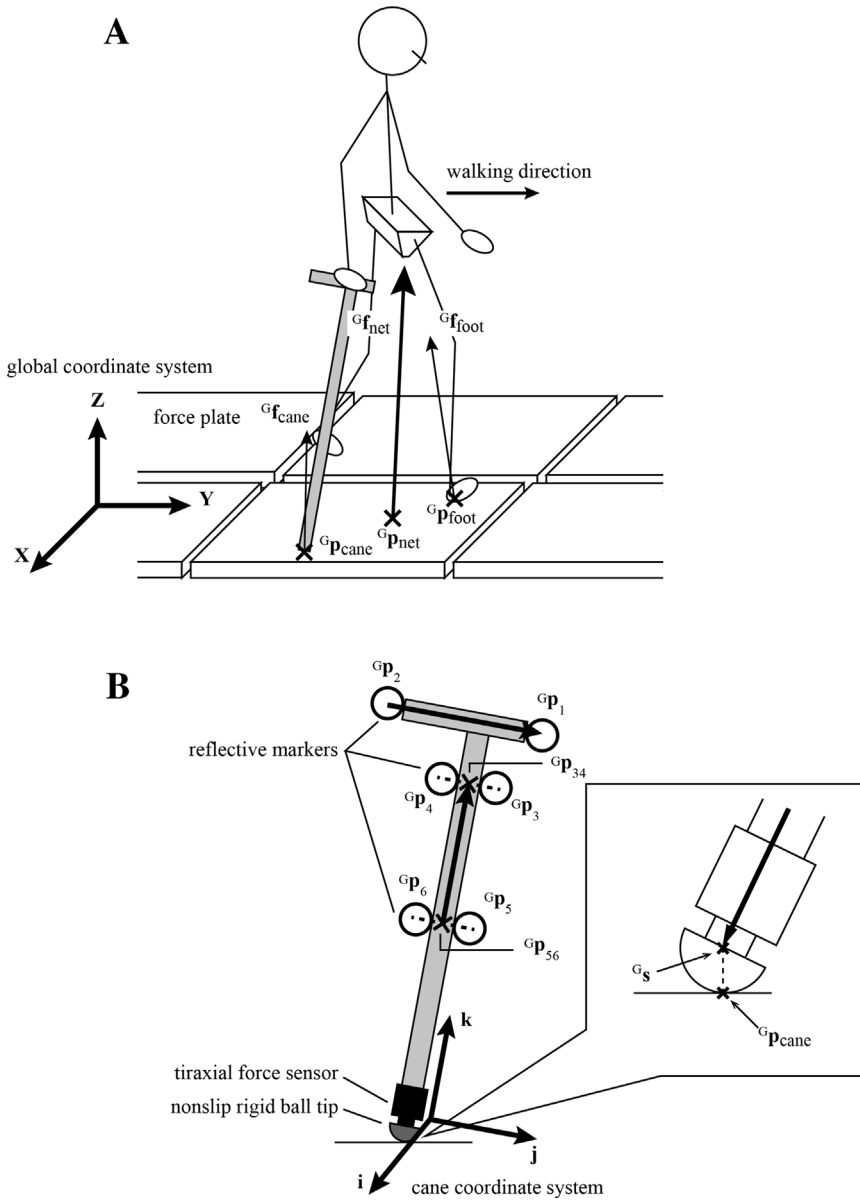
When attempting to conduct kinetic analysis of cane-assisted gait (such as inverse dynamic analysis to evaluate internal forces and joint moments), it is necessary to independently measure the ground reaction forces (GRFs) and centers of pressure (COPs) applied to the foot and the cane. However, if the foot and the cane in the ipsilateral hand are placed on the same force plate simultaneously, the force plate cannot separate the forces acting on the foot and the cane as it records the sum of the forces [13,14]. To overcome this indeterminacy problem of the GRF and COP in cane-assisted gait analysis, an instrumented cane

equipped with a force transducer is necessary to acquire the GRF and COP of the cane. Previous studies have reported analyses of cane-assisted gait using instrumented canes [4,6,8,11,13–21]. However, in most previous studies, the instrumented canes were equipped with a uniaxial force transducer permitting measurement of only a compressive force in the axial direction to the cane, assuming that the ground reaction force is always acting along the cane. This assumption is not necessarily valid, since the hand certainly applies not only a translational force but also a moment on the cane at the handle. For accurate partitioning of the GRFs and the COPs of the foot and cane, an instrumented cane with a triaxial force transducer is necessary.

Previously, Winer et al. [13] presented a theoretical framework to partition the GRFs and COPs during cane-assisted gait using an instrumented cane with a triaxial force transducer. However, they did not evaluate how accurate the presented framework could estimate the GRFs and COPs of the foot and cane. In order to use this partitioning method to actually analyze the GRF and COP in cane-assisted gait, the accuracy and precision of the estimation must be evaluated first.

In the present study, a framework was reestablished to partition the foot and cane GRFs and COPs using a newly developed instrumented

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**Fig. 1.** The indeterminacy problem of the ground reaction force (GRF) and the center of pressure (COP) in cane-assisted gait analysis. (A) If the foot and the cane in the ipsilateral hand are placed on the same force plate simultaneously, the force plate cannot separate the forces acting on the foot and the cane as it records the sum of the forces. An instrumented cane equipped with a force transducer is necessary to acquire the GRF and COP of the cane. (B) Instrumented cane. A triaxial force sensor was inserted into the tip of the cane shaft. Six reflective markers were attached to the cane to obtain the spatial orientation and the tip position of the cane during gait, so that the foot and cane GRFs and COPs can be partitioned based on force and moment equilibrium. A wooden hemisphere (nonslip rigid ball tip) with a diameter of 30 mm was attached to the force sensor so that the cane makes a point contact with the floor. The x and y components of the COP of the cane ( $p_{cane}^x, p_{cane}^y$ ) should be identical to those of the position of the center of the sphere attached to the tip of the cane ( $G_s$ ).

cane with a triaxial force sensor, and the accuracy and precision of the estimated GRFs and COPs were evaluated to demonstrate its applicability during actual cane-assisted gait. To evaluate the accuracy and precision of the partitioned GRFs and COPs, cane-assisted gait was measured using a force plate array and the instrumented cane, and the differences between the estimated (partitioned) and actual (directly measured) GRFs and COPs were evaluated.

## 2. Method

### 2.1. Principle

If the foot and the cane in the ipsilateral hand are placed on a force plate simultaneously, the force plate cannot separate the forces acting on the foot and the cane as it records the sum of the forces (Fig. 1A). However, if the cane force is measured using an instrumented cane, then the foot force can be partitioned from the force recorded by the force plate. Let the force vectors in the global coordinate system recorded by the force plate (net force of the foot and cane) and the instrumented cane be  $G_{f_{net}}$  and  $G_{f_{cane}}$ , respectively (the left superscript denotes the coordinate system in which the vector is represented).

Based on the force equilibrium, the ground reaction force acting on the foot  $G_{f_{foot}}$  can be written as:

$$G_{f_{foot}} = G_{f_{net}} - G_{f_{cane}} \quad (1)$$

The COP can also be partitioned based on the moment equilibrium if the COP of the instrumented cane is known. Let the position vectors of the COP of the force plate (net COP of the foot and cane), the instrumented cane and the foot ground reaction force in the global coordinate system be  $G_{p_{net}}$ ,  $G_{p_{cane}}$  and  $G_{p_{foot}}$ , respectively. The COP of the foot can be calculated based on the moment equilibrium expressed as:

$$G_{p_{net}} \times G_{f_{net}} = G_{p_{foot}} \times G_{f_{foot}} + G_{p_{cane}} \times G_{f_{cane}} \quad (2)$$

Since the z-component of the COP is zero, Eq. (2) can be solved for  $G_{p_{foot}}$  as:

$$\begin{aligned} p_{foot}^x &= (p_{net}^x f_{net}^z - p_{cane}^x f_{cane}^z) / f_{foot}^z \\ p_{foot}^y &= (p_{net}^y f_{net}^z - p_{cane}^y f_{cane}^z) / f_{foot}^z \end{aligned} \quad (3)$$

where  $p_{net}^{x,y}$ ,  $p_{foot}^{x,y}$  and  $p_{cane}^{x,y}$  are the x and y components of  $G_{p_{net}}$ ,  $G_{p_{foot}}$  and  $G_{p_{cane}}$ , respectively, and  $f_{net}^z$ ,  $f_{foot}^z$  and  $f_{cane}^z$  are the z-component of  $G_{f_{net}}$ ,  $G_{f_{foot}}$  and  $G_{f_{cane}}$ , respectively. Error propagation analysis was provided

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