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I. Ait Oumghar, A. Barkaoui & P. Chabrand

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## A procedure and model for identification of passive moment due to uni- and biarticular structures

A. Koussou<sup>a,b</sup>, R. Dumas<sup>b</sup> and E. Desailly<sup>a</sup>

<sup>a</sup>Fondation Ellen Poidatz, Pôle Recherche & Innovation, Saint-Fargeau-Ponthierry, France; <sup>b</sup>Univ Lyon, Univ Gustave Eiffel, Univ Claude Bernard Lyon 1, LBMC UMR T\_9406, Lyon, France

### 1. Introduction

Passive moments (PM), caused by the resistance to deformation of the periarticular tissues in the absence of muscle contraction have been measured in-vivo in several studies (Riener and Edrich 1999; Whittington et al. 2008). A number of previous investigators have identified mathematical models of the passive joint moment-angle relationship. These models suggest that PM substantially contribute to normal gait and are influenced by the stretch of biarticular muscles (Whittington et al. 2008; Koussou et al. 2021).

This influence requires making a large number of tests with several joint angle configurations to identify representative models (Whittington et al. 2008). In this study, we propose and evaluate a procedure and model restricting the number of tested positions.

### 2. Methods

#### 2.1. Protocol and subjects

10 healthy children (mean age:  $11.8 \pm 2.8$ ; 6 males) were tested. The experimental procedure included two components: a passive testing protocol and a gait analysis. Throughout the procedure, 3D kinematics were determined using a marker set placed over specific body landmarks (Plug-in-Gait marker set with two additional markers placed over the iliac bone to take into account that the posterior superior iliac markers are not visible when the patient is lying) and motion analysis system (15 cameras VICON, Oxford, UK).

Firstly, each subject performed a series of gait trials at their preferred speed along a 10m walkway. Ground reaction forces were recorded using four imbedded force plates (2 AMTI, Waterfown, USA and 2 Kistler, Hampshire, UK).

Secondly, a passive testing protocol was designed to obtain continuous joint angle and PM measurements while the subject's joint was slowly manipulated using a 3-D handheld dynamometer through full sagittal ranges of motion (ROM) by an

experimented therapist. The joints were mobilized in 5 different positions to ensure the characterization of the entire lower limb joints taking into account the stretch of the biarticular muscles:

- Ankle mobilized with knee at  $90^\circ$  and  $0^\circ$  (P1 & P2)
- Knee mobilized with hip at  $90^\circ$  and  $0^\circ$  (P3 & P4)
- Hip mobilized with free knee (P5)

EMG was placed over several muscle bellies of the lower limb and used to make sure of the muscle inactivity (Delsys, Natick, USA).

Moreover, muscle-tendon unit (MTU) length and moment arms during passive mobilization or gait trials, was computed via OpenSim, by using the measured kinematics and after having scaled the adult generic model (Rajagopal et al. 2016).

#### 2.2. Model of passive moment

##### 2.2.1 Ankle

At P1, we assumed that only single-joint structures of the ankle produce resistance. Thus, from the measured flexion moment we modelled,  $MA_U$ , the uniaxial moment (UM) of the ankle, relatively to the ankle angle, through a double exponential.

At P2, we assumed that the biarticular structures of the ankle, namely the gastrocnemius lateralis muscles (*Gas*), also produce resistance. Thus, from measured joint moment,  $M_{P2}$ , and by subtracting the UM,  $MA_U$ , we determined  $M_{Gas}$ , the biarticular moment. Then, from the determined *Gas* moment arm over the ankle flexion/extension,  $m_{Gas/a}$ , during P2, we determined  $F_{Gas}$ .

$$F_{Gas} = \frac{M_{Gas}}{m_{Gas/a}} = \frac{M_{P2} - MA_U(\theta_A)}{m_{Gas/a}}$$

Similarly, knowing the *Gas* MTU length during P2, we were able to model this length-force relationship as a simple exponential.

##### 2.2.2. Knee

First, we subtracted to the knee flexion moment at P3 and P4, the moment coming from the *Gas* thanks to the modelled length-force relationship and to the *Gas* MTU length, and moment arm over the knee flexion/extension,  $m_{Gas/k}$ .

Then, we determined  $MK_U$ , the knee UM from these adjusted moments without *Gas* resistance (denoted P3' and P4'). We assumed that  $MK_U$  was null over most of the ROM equal to P3' when an extension moment was present and equal to P4' when a flexion

**Table 1.** Contribution of passive moments to inter-segmental moments.

Joint	Peak	Tot. (%)	Biarticular (%)		
			Gas	Se	Rf
Hip	H1	30.6 ± 18.6		0	3.5 ± 6.2
Knee	K1	45.9 ± 23.7	38.7 ± 27.0	0.2 ± 0.1	-3.2 ± 8.7
	K2	43.1 ± 27.6	16.2 ± 8.3	16.9 ± 8.1	0
Ank.	A1	17.3 ± 6.7	9.2 ± 3.8		

moment was present. These two conditions were encountered at the limits of the ROM, where the biarticular structures are flexed enough not to produce any resistance.

Finally, as previously, we determined knee biarticular resistance,  $F_{Se}$ ,  $F_{Rf}$ , respectively, from semitendinosus ( $Se$ ) and rectus femoris ( $Rf$ ).

$$F_{Se} = \frac{M_{Se}}{m_{Se/k}} = \frac{M_{P3'} - MK_U(\theta_K)}{m_{Se/k}}$$

$$F_{Rf} = \frac{M_{Rf}}{m_{Rf/k}} = \frac{M_{P4'} - MK_U(\theta_K)}{m_{Rf/k}}$$

where  $m_{Se/k}$ ,  $m_{Rf/k}$  are the knee flexion/extension moment arms of the  $Se$  and  $Rf$ .

Knowing their MTU lengths during P3 and P4, we modelled these length-tension relationships with simple exponential.

### 2.2.3. Hip

From the measured hip flexion moment at P5,  $M_{P5}$ , we determined the hip UM,  $MH_U$ . We subtracted to  $M_{P5}$  the hip moment due to the  $Se$  and  $Rf$  that we determined thanks to the modelled length-force relationships and to their MTU lengths, and moment arm over the hip flexion/extension,  $m_{Se/h}$  and  $m_{Rf/h}$ .

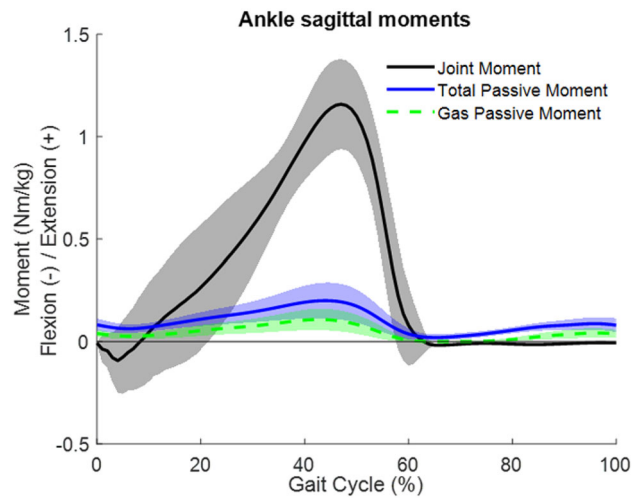
$$MH_U(\theta_H) = M_{P5} - F_{Se}(L_{Se}(\theta_H + \theta_K)) * m_{Se/h} - F_{Rf}(L_{Rf}(\theta_H + \theta_K)) * m_{Rf/h}$$

### 2.2.4. Contribution during gait

PM during gait were estimated using the joint angles and MTU lengths as inputs to the identified models and compared to the inter-segmental moments computed for one gait cycle.

We reported the contribution of the PM to the inter-segmental one at specific phases of the gait cycle corresponding to moment bursts where substantial passive contributions have been shown (Whittington et al. 2008):

- A1: Peak ankle stance-phase extension moment
- K1: Peak knee stance-phase flexion moment
- K2: Peak knee swing-phase flexion moment
- H1: Peak hip stance-phase flexion moment



**Figure 1.** Ankle moments during gait.

## 3. Results and discussion

Table 1 presents the contributions detailed between uni- and biarticular structures.

It appears that PM contribute at different instants of the gait cycle in proportions consistent with the literature (Koussou et al. 2021). These contributions are influenced by biarticular muscles.

At the ankle,  $Gas$  produces around the half of the passive moment at A1 (Figure 1). At the knee,  $Gas$  also produces an important part of the PM at K1 and K2, while  $Se$  plays a role only at K2 by controlling knee extension. Interestingly, at these two peaks,  $Rf$  seems to have little influence on knee PM.

Finally, at H1 we can note that the major part of the PM comes from uniarticular structures, while  $Se$  and  $Rf$ , being little stretched, produce only little resistance.

One limitation of the procedure is the use of a scaled adult model. However, no Hill-type parameters are used, only MTU length and moment arms.

## 4. Conclusions

We proposed a procedure and passive model taking into account the biarticular muscles while restricting the number of positions to be tested (5 vs 12 in Whittington et al. 2008).

Passive structures can contribute substantially at different instants of the gait cycle with difference between uni- and biarticular structures.

A quantitative assessment of passive elastic mechanisms present in normal walking could therefore provide an improved basis for investigating factors underlying pathological gait.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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**KEYWORDS** Joint resistance; stiffness; passive moment

 [axel.koussou@fondationpoidatz.com](mailto:axel.koussou@fondationpoidatz.com)