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The Projection of the Ground Reaction Force as a Predictor of Internal Joint Moments

RICHARD P. WELLS, Ph. D.

Assistant Professor
Department of Kinesiology
University of Waterloo
Waterloo, Ontario
Canada N21 3G1

ABSTRACT

The projection of the ground reaction force vector is commonly used in clinical and rehabilitation settings to predict internal moments generated at the hip, knee, and ankle during walking. The results of using this convenient estimate are compared with those of a more complete measure (link segment method) in order to illustrate the differences quantitatively. Though both have intrinsic potential for errors, the author considers the link segment method much more accurate—and thus takes it as a standard against which the projection method may be judged. Thus, he defines differences between values obtained by the two methods as "errors" of the projection method. It is found that while the errors at the ankle are negligible, the errors at the knee and especially at the hip (and especially around the times of pushoff and heel contact) can give moments of incorrect magnitude or moments of the wrong polarity, especially at higher speeds.

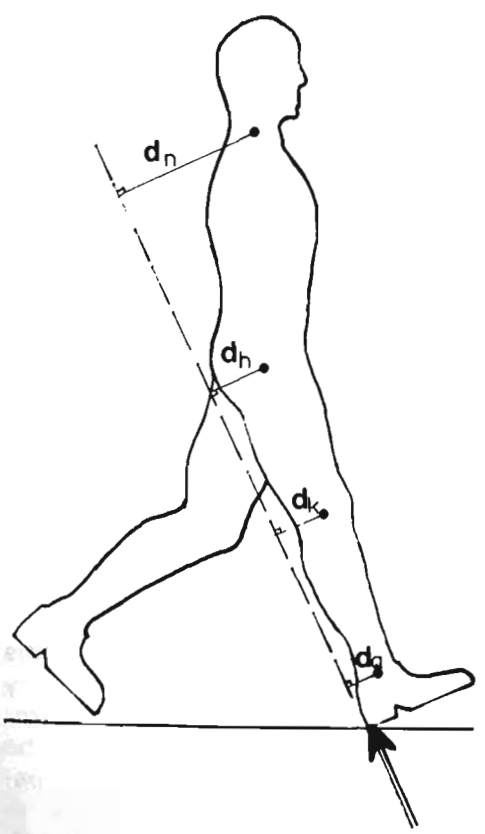


FIGURE 1.
The projection of the ground reaction force used as prediction of internal joint moment. The distance of the projection from the relevant joint centre gives the magnitude of the net joint moment. In this situation, one would predict a net joint moment acting in dorsiflexion at the ankle, in extension at the knee, and in flexion at the hip.

INTRODUCTION

Joint moments at the ankle, knee, and hip are commonly used in clinical and rehabilitation settings as quantified input to the process of patient assessment. These net internal joint moments are primarily the result of muscular action about the joints of the leg during gait. These data are thus very useful to the prosthetist or clinician.

Unfortunately, it is not easy to obtain the net joint moments over an entire walking cycle using the link segment analysis performed by Bresler and Frankel in their classic paper (1). The process is expensive and/or time consuming, modern methods notwithstanding. As a result, simpler methods of estimating the net joint moments in the leg have been used; one of them is the projection of the ground reaction force vector. The purpose of this paper is to assess the accuracy of that measure for predicting the net joint moments during walking.

The distance of the projection of the ground reaction force vector from a joint centre is frequently taken as a measure of the moment or torque acting about a lower limb joint (Fig. 1). The measure is only approximate, and the magnitude of the difference between it and the result of a more complete study will increase as the moments at joints higher on the body are estimated. Consider the following examples. Figure 1 represents a person with the ground reaction force vector passing through the centre of pressure of the foot. It would be common practice to project the ground reaction force and, using the distance from the joint centres at the ankle, knee, and hip (da, dk and

dh) to estimate each net internal joint moment as the opposite of the external moment estimated from the magnitude of the ground reaction force and the perpendicular distance from the projected vector to the respective joint centre.

The fundamental incorrectness of that method can be seen by taking the method to extremes. If one were to attempt to use the method to estimate the joint moment at the neck, one can see that the projection of the ground reaction vector passes perhaps 0.5 m from the neck (dn) at around the time of heel contact, giving an estimated moment of around 400 newton metres (N·m) for a 70 kg person. In reality, of course, the moments in this joint are very small.

Despite the incorrectness of the method, some investigators have chosen to use it, but only after a preliminary analysis. For instance, Cappozzo et al. (2) found that for prediction of the knee moment on the prosthetic side in A/K amputees, the errors introduced by using the projection of the ground reaction force amounted to no more than 10 percent. It should be noted, however, that the prosthesis is purposely made lighter than a sound limb, and their data indicated a slower-than-normal walking speed.

Although most persons involved in gait assessment who use net joint moments realize that the projection of the ground reaction force is only an estimator of joint moments, they may not realize the magnitude of the errors involved. To explore these errors, the estimated joint moments in the lower limb will be compared with those obtained by the more complete (and presumably more accurate) method of segment-by-segment analysis.

METHODS

Kinematic and forceplate data on eight subjects were taken from a data bank in the Locomotion Laboratory of the University of Waterloo. The methods for obtaining and reducing these data were described by Winter and Robertson (3). Briefly, they are as follows:

Each subject wore his/her own footwear, and was asked to walk along a raised walkway which was 10 m long and raised 30 cm to accommodate a triaxial force platform located near the middle. A tracking cart carrying a TV camera (for guidance purposes) and a cine camera was moved alongside the subject at a range of 4 m for several strides before and after stepping on the force plate. Background markers on the wall behind the walkway gave fixed reference so that body coordinates could be properly scaled to an absolute reference frame. Body and background coordinates were extracted using a Numonics Digitizer interfaced to a NOVA II computer. These raw coordinate data were scaled and corrected for parallax and then transferred to a IBM 370 computer along with the sychronized plate data comprising the vertical and horizontal (anterior-posterior) forces and the centre of pressure in the plane of progression.

Prior to analysis, the coordinates were digitally filtered using a fourth-order, zero lag, low-pass Butterworth filter cutting off at 5 Hz. The validity of the filtering and subsequent finite difference calculations of velocity and acceleration is supported by the study of Pezzack et al. (4). Anthropometric data were obtained for each subject, using tables provided by Dempster (5) based on subject's height and weight.

The subjects, who walked at a variety of speeds, included both normals and patients with gait disfunction. The net joint moments at the ankle, knee, and hip were computed from the same data in two ways:

1. By analysis of a model of seven linked segments from the contact foot with known ground-reaction forces. This link segment analysis then proceeded up the lower limb to the trunk. The procedure is well known: Bresler and Frankel (1).
2. By a projection method which involves computing the net joint moment from the ground-reaction force and simultaneous joint positions (Fig. 1). This is equivalent to visualizing the position of the ground reaction force vector with respect to the joint under consideration.

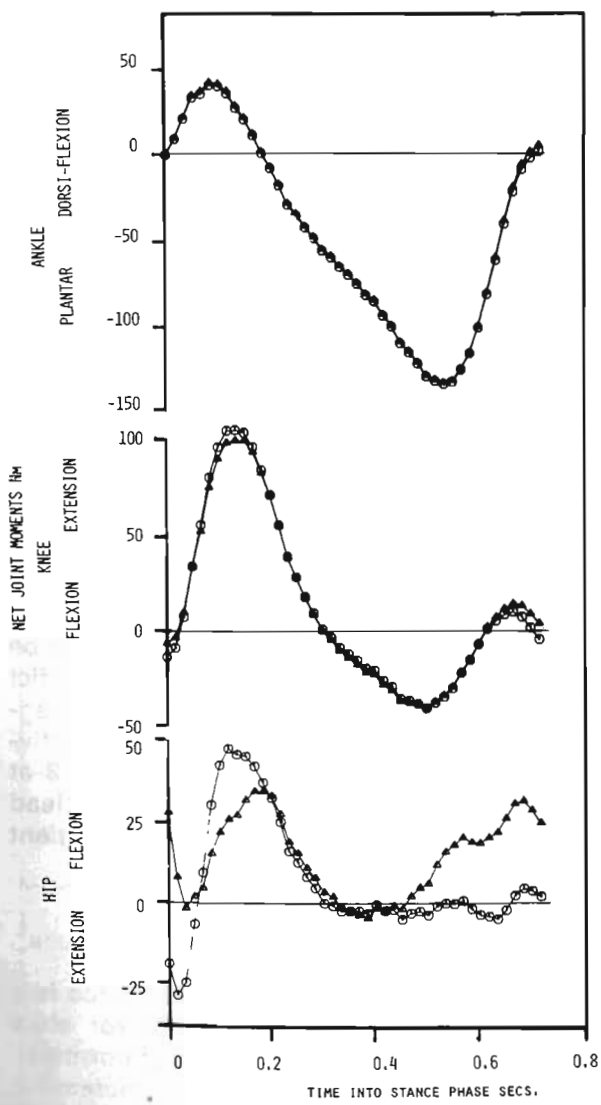
It should be noted that both methods use not only the same photographic data but the same ground-reaction force, measured using a force platform. The link segment model, however, takes into consideration the gravitational and inertial forces acting on the foot, leg, and thigh as the analysis progresses up the lower limb. The projection method neglects these forces completely. Of course, in order to calculate the gravitational forces and the inertial forces and moments caused by limb segment accelerations, the various anthropometric parameters of the segments must be measured or estimated. The values of these parameters are usually approximations and thus introduce error into the calculations. This fact notwithstanding, the values obtained from the link segment model are considered by this author to be the best estimates presently available, and will be taken as a standard by which the results of the projection method can be judged. The difference between the values obtained by these two methods will therefor be termed the "error of the pro-

jection method."

This view is supported by validation studies recently performed on the link-segment model used, Pezzack and Norman (6). The basis of their validation can be summarized thus: The total ground reaction force can be calculated from segmental positions and accelerations taken from cine film, together with estimated segment weights and moments of inertia for each film frame during stance. This computed total ground-reaction force can be compared with the actual ground-reaction force, as measured by a force plate. The differences between results obtained with the two methods indicate the accuracy of the analysis or of the anthropometric parameters—or probably of both. The maximum differences in a standing broad jump were of the order of 10 to 15 percent. The differences during walking have been found to be less than this.

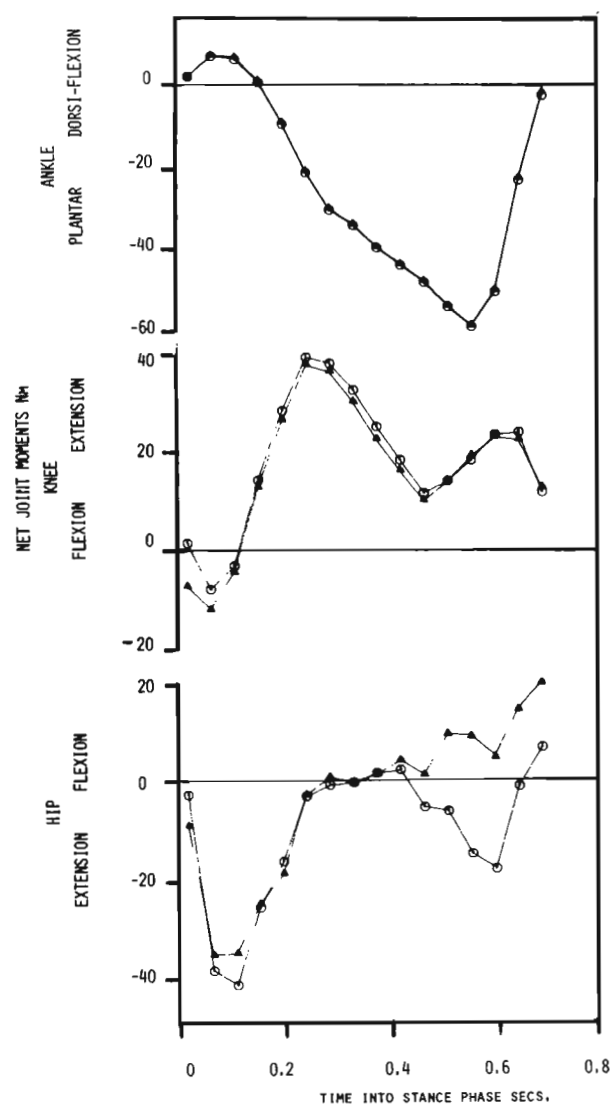
RESULTS

Figure 2 shows the joint-moment/time histories during the stance phase for a normal athletic subject walking at 1.4 m/s. Figure 3 shows the same information during the stance phase for a patient with a total hip arthroplasty walking at 1.19 m/s. In contrast, Figure 4 shows the joint-moment/time



Δ Joint Moments From Link Segment Model
O Joint Moments Predicted From Ground Reaction Force Vector Alone

FIGURE 2.
Comparison of link-segment and predicted joint moments for a normal subject walking at 1.4 m/s.



Δ Joint Moments From Link Segment Model
O Joint Moments Predicted From Ground Reaction Force Vector Alone

FIGURE 3.
Comparison of link-segment and predicted joint moments for a subject with a total hip replacement walking at 1.19 m/s.

histories for a small child with spinal bifida and flail ankles (but no orthoses) at a velocity of only 0.27 m/s.

Table 1 reports the results for all eight subjects, and presents a summary of the differences in joint moments. There are also brief descriptions of the subjects and trial conditions. The maximum error is the maximum difference between the moments calculated using the link segment model and the moment calculated using the force plate vector and photographic data alone (projection method). The root-mean-square (rms) error over stance phase is computed using the differences defined above.

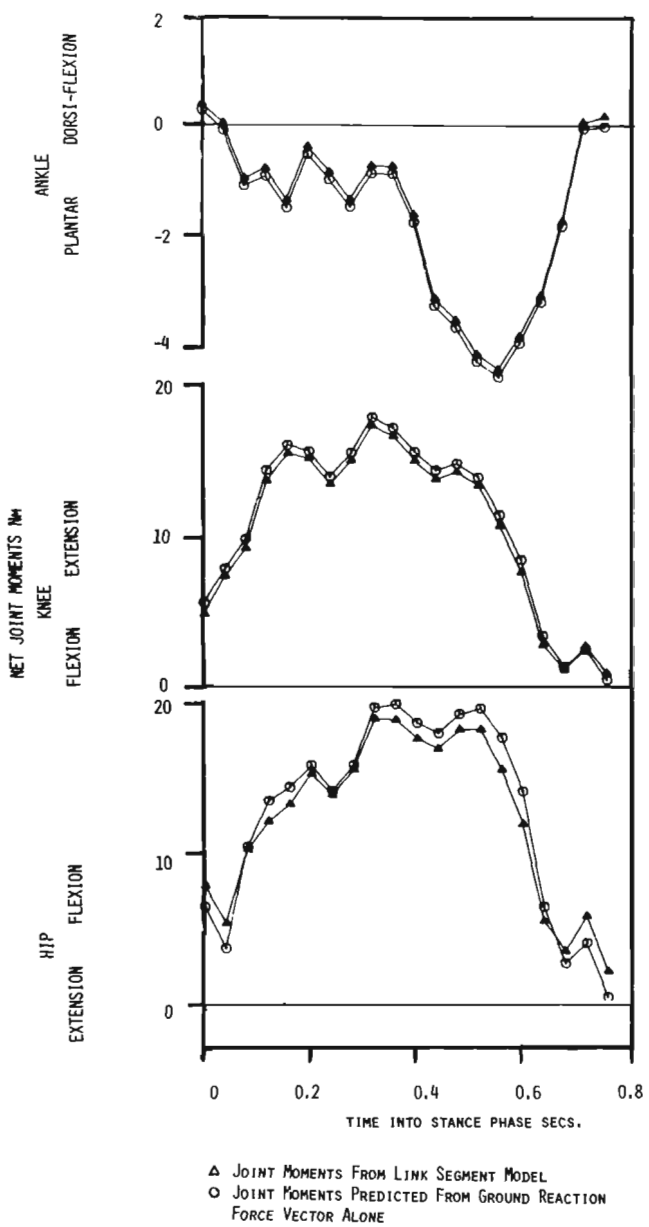


FIGURE 4.
Comparison of link-segment and predicted joint moments for a subject with spina bifida walking at 0.27 m/s.

DISCUSSION

It has been noted that projecting the line of action of the ground reaction force to obtain a measure of joint moment is an approximate measure because it neglects the weight and inertia force contributions of the limbs between the ground and the joint under consideration. From the above it would be expected that the joint moment estimates would become poorer as the inertia forces increase (higher accelerations associated with velocity/cadence) and as the forces due to segment weight between the ground and the joint increase (estimating at the knee and, worse, at the hip).

An inspection of Table 1 shows both these effects. Both the maximum errors and the rms errors typically increase as one goes from the ankle to the knee to the hip. These errors also tend to increase as the velocity of walking increases, giving correlation coefficients between error and walking speed of $r = 0.69$, $p < .05$ and $r = .67$, $p < .05$ for the maximum and rms errors respectively. The normal subject WN21F, for instance, shows the highest velocity and the largest errors at the hip. It is noticeable that the largest differences can be seen around heel contact and push-off, when the segment accelerations are greatest and the segments also are most inclined so that gravitational effects are greatest.

The histories of net joint moment vs. time are often used to draw conclusions about muscle activity. The projection method has been seen to give net joint moments of incorrect magnitude. This difference in magnitude alone is not too serious, but the projection method can also indicate moments of the wrong polarity. If one examines the data for the normal subject, Figure 2, it can be seen that around 0.6 seconds one would predict slight hip extensor activity whereas the link segment analysis indicates moderate hip flexor activity. A similar problem can be seen in Figure 3 at the hip, again around 0.6 seconds. This could lead to wrong conclusions being drawn during patient assessment.

CONCLUSIONS

The projection of the ground reaction force is a good predictor of net joint moments for slow walking (more typical of patients than of normals). Increasing the velocity of gait results in increasing errors, especially at the hip. It can be concluded that it is a useful clinical *estimate,* but care must be taken when using the method in normal or faster speed walking, or for estimating moments at the hip joint. The influences of mass and its distribution, e.g., below normal in a prosthesis or an

atrophied limb, or above normal with a major orthosis, remain to be investigated.

REFERENCES

1. Bresler B, and Frankel JP: The Forces and Moments in the Leg During Level Walking. Trans ASME 72:27–36, 1950
2. Cappozzo A, Leo T, and Cortesi SS: A Polycentric Knee-Ankle Mechanism for Above-Knee Prostheses. J Biomech 13(3):231-239, 1980.
3. Winter DA, and Robertson GE: Joint Torque and Energy Patterns in Normal Gait. Biological Cybernetics 29:137–142, 1978.
4. Pezzack JC, Norman RW, and Winter DA: An Assessment of Derivative Determining Techniques Used for Motion Analysis. J Biomech 10:377–382, 1977.
5. Dempster WT: Space Requirements of the Seated Operator. Wright Patterson Air Force Base, Ohio: US Air Force, 1955. (WADC Tech Rept 55–159.)
6. Pezzack JC, and Norman RW: A Validation of the Joint Reaction Force and Resultant Moment Output of an "N" Link Plane Motion Model of the Human. In press; Baltimore, University Park Press, Biomechanics VII, (International Seminar on Biomechanics) 1980.

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Subject	Age	Wt. kg	Ht m	Sex	Remarks	Cadence Step/min	Velocity m/sec	Joint	Max. Error Nm	Mean Error Nm	Stand. Dev. of Error Nm
WN21F	25	77.5	1.79	M	Normal	106	1.42	Ankle Knee Hip	3.7 8.5 45.8	1.2 -0.2 7.7	1.4 3.3 16.7
WN35L	22	55.75	1.56	F	Normal	107	1.24	Ankle Knee Hip	.9 -5.4 11.4	.3 -.1 0.2	.4 1.2 4.5
WN35M	"	"	"	"	"	111	1.26	R.Ankle R.Knee R.Hip	.7 -4.3 10.2	.3 -.3 0.1	.4 1.0 3.9
WP45D	21	53	1.54	F	Traumatic Total Hip Replacement 3 yr Postop	114	1.19	Ankle Knee Hip	.9 -7.5 21.5	.1 -.5 2.4	.2 1.4 5.8
WP12C	72	67	1.53	F	Right Medial Knee Replacement 3 yr Postop	109	1.10	R.Ankle R.Knee R.Hip	1.7 -13.9 -21.7	.5 -.3 2.6	.6 2.6 6.6
WP17B	32	74.4	1.87	M	Right B/K Amputee SACH Foot Prosthetic Side	93	1.13	R.Ankle R.Knee R.Hip	1.2 -5.3 15.9	.9 .2 5.3	.6 1.2 7.0
WP42B	38	61.5	1.59	F	Patellectomy	101	1.01	Ankle Knee Hip	0.9 3.5 13.9	.3 -1.7 0.3	.4 2.6 5.3
WP35C	57	66	1.76	F	Spinal Fusion Total Hip Replacement	67	0.46	Ankle Knee Hip	.8 -5.7 -5.0	0.5 -2.5 0.2	.5 2.9 2.7
WP25G	7	21	1.12	F	Spina Bifida with Flail Ankles	100	0.27	Ankle Knee Hip	.2 .7 -1.9	.1 -.4 -0.3	.1 0.5 1.1

TABLE 1.—Comparison of results using link-segment analysis, and joint moments predicted by the projection method, for all subjects. Differences between results obtained with the two methods are characterized as "errors" of projection-method results.