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A Static Biomechanical Load Carriage Model

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Summary

A two-dimensional biomechanical model of a backpack has been developed which incorporates the primary forces at the shoulder and waistbelt contact points. The model had been validated using instrumented manikins in laboratory experiments. The computer-based formulation allows the user to specify parameters for certain pack features, such as pack mass and volume, and it predicts the resulting contact forces on the bearer. By treating some parameters as decision variables, such as the location of attachment of the shoulder straps to the pack, the model can be used as an optimization tool to achieve a specified objective, such as minimizing the total forces on the bearer. A base case analysis and some variants illustrate this type of analysis. For the example provided, it is not possible to find a feasible solution within the prescribed shoulder-to-waist load ratio. By freeing up other variables, several alternative solutions are presented. This model can be used to easily examine trade-offs in certain pack design decisions.

Introduction

Backpacks are common devices to increase human load carriage capabilities, but when heavily loaded can still place a great burden on the bearer. Many design improvements have been made over the past decades, but more research is still required to fully understand the implications of the associated static and dynamic forces. Parametric analysis of personal load carriage systems allows for increased understanding of relationships between system design characteristics and the impact of these design features on the bearer. A computer-based static biomechanical model of a backpack has been developed to represent the interaction between the pack and the bearer at the principal contact points.

Optimization of the biomechanical model yields the best location for attaching the suspension system components. Various objectives can be considered, such as achieving the best load balance between the shoulders and waist, or minimizing the transverse shear at the lumbar level, which is often associated with discomfort and pain. In the current formulation, the objective is to minimize the sum of the three primary forces acting on the bearer by the pack: the normal force at the shoulders, the vertical force on the hips and the lateral shear on the back at the wasitbelt. A limited set of runs applied to a Base Case backpack illustrates the trade-offs inherent in design decisions.

Literature Review

The literature on personal load carriage is quite broad, and generally falls into one of three categories: physiological studies, biomechanical studies, and subjective appraisal studies. Most of the biomechanical studies concentrate on gait analysis (e.g. DeVita et al., 1991). As there are several comprehensive survey articles on various aspects of load carriage (e.g. Rorke, 1990; Haisman, 1988; Pelot et al., 1995), the following review focuses on some articles directly relevant to the model described in this paper.

Almost all studies consider the effects of load carriage on the subject through experimentation, and the backpack is part of the pack/person system. Articles examining the isolated pack as a system (static or dynamic) are almost non-existent, however Bobet and Norman (1984) develop a free-body diagram of the trunk/pack system while examining the effects of load placement using EMG. Furthermore, few studies concern themselves with load carriage design details. Exceptions include Bloom and Woodhull-McNeal (1987) who compare internal and external frame packs, and other researchers who consider a double-pack system (e.g. Kinoshita, 1985; Johnson et al., 1995). Certain pack elements are evaluated in isolation, such as the shoulder model presented by Holewijn (1990). Field trials comparing pack features are commonly reported in relevant magazines (e.g. Jenkins, 1992).

In order to establish limitations on contact forces, information is required on the effects of these pressures on the bearer. An article by Sanders et al. (1995) provides an overview of skin response to mechanical stress, while particular injuries arising from load carriage pressures are described in several articles (e.g. Bessen et al., 1987). Studies by Stevenson et al. (1996) have measured strap forces and pressures and correlated them with measures of human discomfort, thereby establishing threshold values on the force levels that may cause discomfort.

The body lean angle under load carriage depends on several factors including pack mass, pack design, level of fatigue, and terrain. Results of such investigations include those by Bloom et al. (1987) and Stevenson et al. (1996). Five to ten degrees is a typical range, but the user may specify this parameter in the model described in this paper.

Since the goal of this biomechanical model is to choose values for certain variables that will optimize an objective, such as minimizing total contact forces, the reader may consult a text such as Winston (1996) to review optimization and formulation in general, linear programming in particular, and non-linear programming, as some optional constraints in the present model introduce non-linear relationships.

Biomechanical Model

A free body diagram of a rigid model of a typical rucksack is shown in Figure 1. The notation is defined at Table 1. The suspension system elements have been numbered from the top down for convenience. Thus the upper shoulder strap's location (d_1), attachment angle (θ_1) and tension (T_1) are consistently subscripted. The subscript ‘2’ refers to the lower shoulder strap portion, and ‘3’ is reserved for certain waistbelt variables. The entire figure and its associated reference coordinates are angled at ß degrees from the vertical to reflect the normal body lean that occurs under heavy loading conditions.

When conducting a parametric analysis, many of the values in the diagram may be treated as variables, to determine the impact of changing them. For the evaluation of a specific pack under given loading conditions, all fixed parameters must be specified and the model is solved for the unknown forces T_1, T_2, F_Z and F_X. To solve for these using the three force balance equations, note that a relationship exists between T_1 and T_2. By modelling the shoulder as a pulley with friction, T_1 and T_2 are related by the friction coefficient and the wrap angle, as shown by equation (1) below (see MacNeil, 1996). The wrap angle α depends on several pack dimensions, notably the attachment points of the upper and lower shoulder straps, shoulder radius, and shoulder-pack distance, as shown in Figure 2 and equations (6) through (10).

Table 1. Notation for Static Biomechanical Model

Suspension System Element	**Notation**	**Definition**
Orientation	X	coordinate along pack depth (positive out)
	Z	coordinate along pack height (positive up)
Pack Container	W	the force of the mass of the pack
	v_X, v_Z	position of Centre of Mass
	h_X, h_Z	dimensions of pack container
Bearer	d_4	distance: waistbelt centre to shoulder centre
	d_5	distance: pack back to shoulder centre
	r	radius of shoulder
	r_H	radius of hips
	ß	body lean angle
	γ_1	anatomical lower back angle from vertical
	γ_2	anatomical hip angle from vertical
Waistbelt	T_3	tension in waistbelt
	d_3	distance of waistbelt from bottom of pack
	T_{3C}	compressive force that T_3 applies around the hips
	T_{3C}^N	component of T_{3C} normal to the hips
	T_{3Cf}	force of friction due to T_{3C}
	F^B_Z	lift provided by waistbelt resting on hips
	μ_B	coefficient of friction of waistbelt on hips
	t	thickness of waistbelt
	h_B	height of waistbelt
Shoulder Straps	T_1	tension in upper shoulder straps (LHS and RHS summed)
	T_2	tension in lower shoulder straps (LHS and RHS summed)
	d_1	distance: waistbelt centre to attachment point of upper shoulder strap
	d_2	distance from waistbelt centre to attachment point of lower shoulder strap
	θ_1	upper shoulder strap angle from pack normal
	θ_2	lower shoulder strap angle from pack normal
	α	angle subtended by contact of strap wrapped around shoulder
	μ_S	coefficient of friction of strap on shoulder
	S^N	net force acting normal to the shoulder
Lumbar area	F_X	reaction force of lower back on pack in X-direction
	F_X^N	component of F_X normal to the lower back
	F_{Xf}	force of friction due to F_X
	F^L_Z	lift on the pack from friction and angle at lower back
	μ_L	coefficient of friction of lumbar pad on lower back
	F_Z	total lift force at lumbar contact point of pack

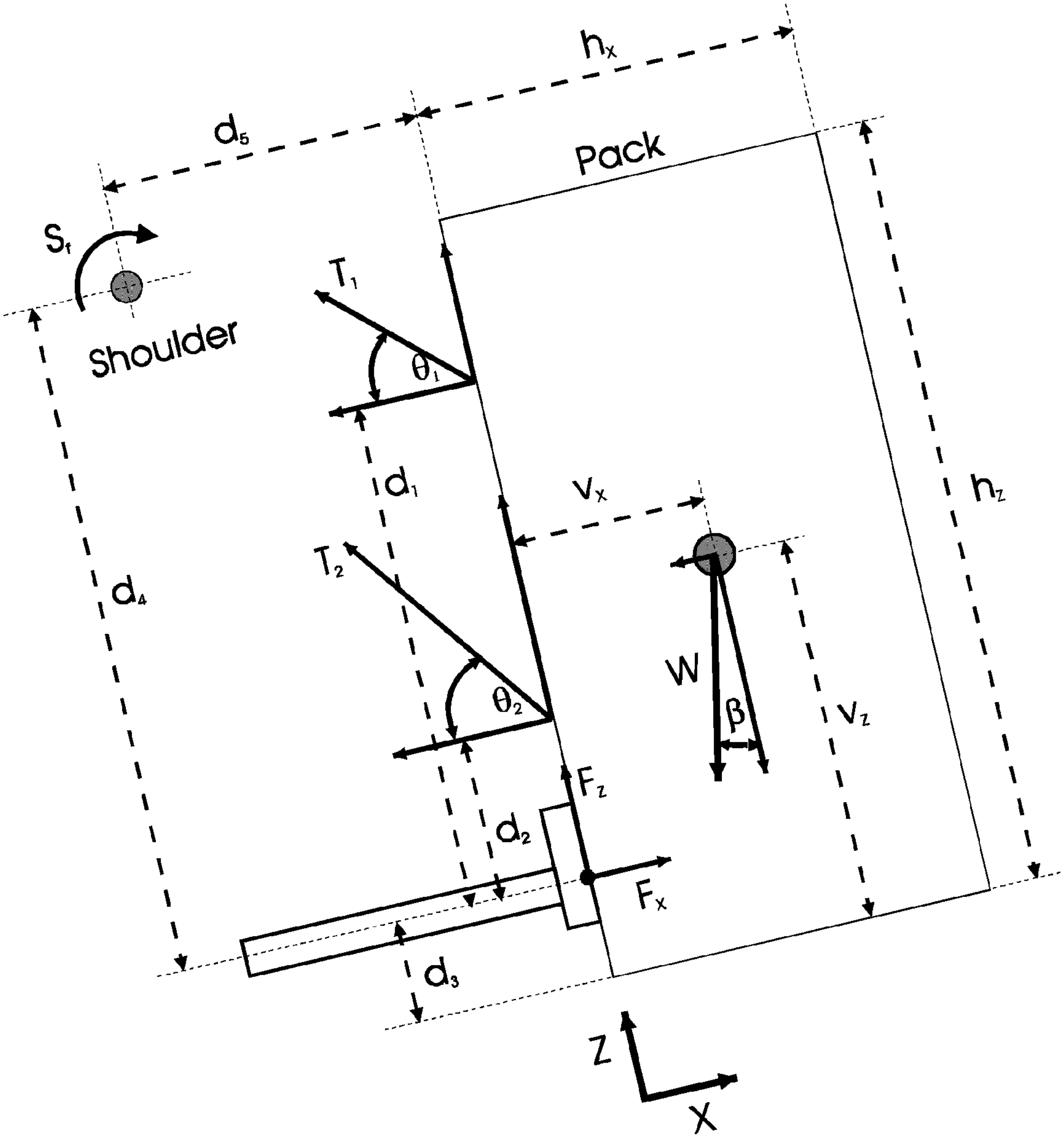

Figure 1. Rucksack free-body diagram with trunk lean

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