International Journal of Industrial Ergonomics, 2 (1988) 179–182
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

MODELLING OF A CARPET INSTALLER KNEE-KICKER

Y.S. Liu, R.L. Huston

Department of Mechanical and Industrial Engineering, University of Cincinnati, Cincinnati, OH 45221 (U.S.A.)

and A. Bhattacharya

Biomechanics-Ergonomics Research Laboratory, Department of Environmental Health, University of Cincinnati, Cincinnati, OH 45221 (U.S.A.)

(Received January 9, 1987; accepted in revised form March 23, 1987)

ABSTRACT

A model of a carpet installer's knee-kicker is presented. A "knee-kicker" is a tool used by a carpet installer in stretching a carpet. It consists of a rod with a knee pad on one end and barbs on the other end. During use, the tool is placed on the carpet and it is then impacted on the knee pad by the suprapatellar region of the knee of the carpet installer. The tool is modelled by a viscoelastic solid representing the knee pad and an elastic column representing the rod. The behavior of this system during a kicking cycle can be described by a pair of differential equations. Solutions to these equations are also presented. The results are compared with experimental data and with results from a biodynamic model of the carpet installer. It is found that the typical knee-kicker pad does little to attenuate the impulse of the kick stroke. Recommendations for improving the pads are suggested.

INTRODUCTION

Studies of musculoskeletal disorders of occupational origin have mainly been concentrated in the upper extremeties and lower back. However, for carpet installers, recent information (Tanaka et al., 1982) shows that there is a high level of knee injuries measured in terms of percent claims per percent workforce.

Studies conducted at the University of Cincinnati show that carpet installers spend 71% of their work period using a "knee-kicker" to stretch the carpet (Bhattacharya et al., 1985). A knee-kicker is a tool in the form of a rod with a pad on one end and barbs on the other end. In using a knee-kicker the worker places the tool on the carpet and then impacts the knee-kicker pad with the suprapatellar region of his or her knee. The forces generated are impulsive in character. Animal studies simulating this phenomena suggest that the repetitive impacts to the knee could explain the high level of knee morbidity found among carpet installers (Radin et al., 1971).

There is a pressing need to develop new knee-kicker pad designs which will reduce the impact loading on the knee and thus reduce the long-term injuries sustained by carpet installers. To develop such designs it is necessary to first develop a procedure for accurately measuring the impact forces exerted on the knee. In this paper we present a procedure for modelling the knee-kicker and its mechanical properties. Using this proce-

0169-8141/88/$03.50

dure we can predict the force magnitudes during the knee/pad impact. The procedure is based upon both analytical and experimental techniques used to measure the system behavior.

The balance of the paper describes the procedure and typical results. It is divided into four parts with the first of these describing the modelling. The next part describes the experimental procedures. Typical results are given. The analysis is presented in the subsequent part and the final part provides a discussion and concluding remarks.

MODELLING

The model of the knee-kicker is shown in Fig. 1. It consists of a rod containing a load cell. On one end of the rod there is a plate A with barbs to catch and stretch the carpet. At the other and there is a viscoelastic knee pad B.

The pad may be modelled mechanically as a spring-mass-damper as shown in Fig. 2. In this representation m is the mass of the pad, k is its stiffness, c is the damping coefficient, $f(t)$ is the force exerted by the knee, $p(t)$ is the force transmitted to the carpet (as measured by the load cell), and t is time. Considering free-body diagrams of the pad and the interface with the load cell we obtain the equations:

$$m\ddot{x} + c\dot{x} + kx = f(t) \quad (1)$$

and

$$c\dot{x} + kx = p(t) \quad (2)$$

where x measures the displacement of the center of the pad relative to the load cell interface (overdots designate time derivatives).

By taking the Laplace transform of eqns. (1) and (2), by assuming zero initial conditions, and by eliminating $x(s)$ (the transform of x) we obtain the transfer relation:

$$F(s) = \frac{ms^2 + cs + k}{cs + k} P(s) \quad (3)$$

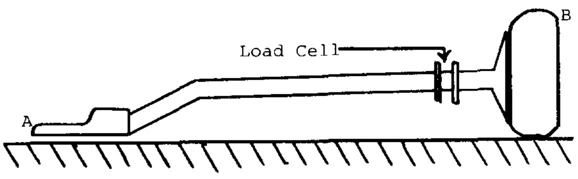

Fig. 1. Knee-kicker model.

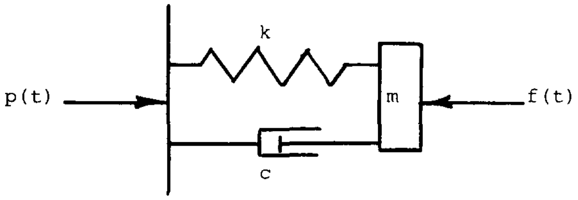

Fig. 2. Mechanical model of knee-kicker.

where s is the transform variable and $F(s)$ and $P(s)$ are the transforms of $f(t)$ and $p(t)$.

EXPERIMENTAL MEASUREMENTS

To develop the mechanical model, the pad from a knee-kicker was tested. The physical (dynamic) properties were determined using a Hewlett-Packard Structural Dynamics Analyzer (Model 5423A). The stiffness of the pad was measured using a structural compression testing machine.

The results show that the stiffness was dependent upon the compressive load L:

$$k = \begin{cases} 2977 \text{ lb/ft} & 0 \leqslant L < 40 \text{ lb} \\ 1336 \text{ lb/ft} & 40 < L \leqslant 100 \text{ lb} \\ 2726 \text{ lb/ft} & 100 < L \leqslant 150 \text{ lb} \end{cases} \quad (4)$$

(1 lb = 4.448 N and 1 lb/ft = 14.6 N/m)

The dynamic properties were found to be:

$$\omega_n = 1125.4 \text{ rad/s and } \zeta = 10.25, \quad (5)$$

where ω_n, the natural frequency, is defined to be:

$$\omega_n = \sqrt{k/m}, \quad (6)$$

and where ζ, the damping ratio, is defined to be

$$\zeta = c/2m\omega_n, \quad (7)$$

and the product $2m\omega_n$ is sometimes called the "critical damping".

Using the results of eqns. (4) and (5) and the definitions of eqns. (6) and (7), the stiffness, effective mass, and damping can be determined. The results are given in Table 1.

Next, to determine the knee force $f(t)$, the impulsive force $p(t)$ was measured by the load cell for typical kick motions. The results are shown in Fig. 3.

TABLE 1

Mechanical properties of a knee-kicker pad

Model parameter	Force ranges		
	0–40 lb	40–100 lb	100–150 lb
Effective mass			
(slug) (14.6 kg)	0.00236	0.00106	0.00214
Stiffness k			
(lb/ft)			
(14.6 N/m)	2977	1336	2726
Damping c			
(lb s/ft)			
(14.6 N s/ft)	0.542	0.243	0.497

Through use of curve fitting techniques the impulse function of Fig. 3 may be approximated by the expressions:

$$p(t) = \begin{cases} At/t_1 & 0 \leqslant t \leqslant t_1 \\ Ae^{-b(t-t_1)} & t \geqslant t_1 \end{cases} \tag{8}$$

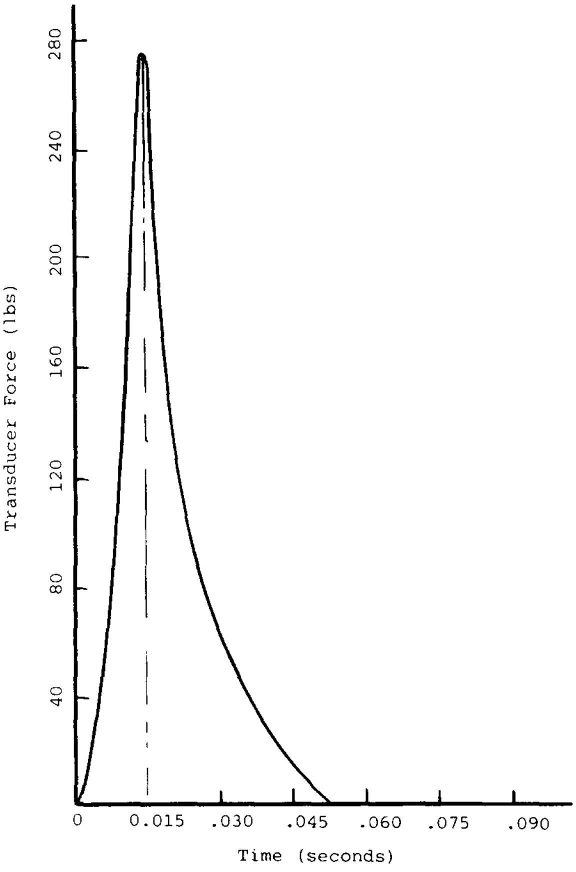

Fig. 3. Force transducer response.

where A is the maximum value of $p(t)$, t_1 is the time when the maximum occurs and b is a constant. From Fig. 3 the values of A, t_1, and b are found to be:

$$A = 274 \text{ lb} \qquad t_1 = 0.015 \text{ s} \qquad b = 80/\text{s} \tag{9}$$

Finally, by taking the Laplace transform of $p(t)$ in eqn. (8), by using eqn. (3), and by evaluating the inverse transform, $f(t)$ is found to be:

$$f(t) = \begin{cases} At/t_1 + (Am/ct_1)\, e^{-kt/c} \\ \quad 0 \leqslant t < t_1 \\ A(k - bc + mb^2)/(k - bc)\, e^{-b(t-t_1)} \\ \quad -(Amk^2/(k - bc)c^2)\, e^{-[(kt/c)-bt_1]} \\ \quad t \geqslant t_1 \end{cases} \tag{10}$$

Hence, by using the values of m, k, c, A, and b of Table 1 and eqn. (9), the knee force $f(t)$ becomes:
(i) For $0 < f \leqslant 40$ lb$_f$

$$f(t) = \begin{cases} 274t/t_1 + (5280/t_1)\, e^{-5493t} \\ \quad 0 < t \leqslant t_1 \\ 275.4\, e^{-80(t-t_1)} - 6622\, e^{-(5493t-80t_1)} \\ \quad t > t_1 \end{cases} \tag{11}$$

(ii) For $40 < f \leqslant 100$ lb$_f$

$$f(t) = \begin{cases} 274t/t_1 + (5280/t_1)\, e^{-5498t} \\ \quad 0 < t \leqslant t_1 \\ 275.4\, e^{-80(t-t_1)} - 6668\, e^{-(5493t-80t_1)} \\ \quad t > t_1 \end{cases} \tag{12}$$

(iii) For $f > 100$ lb$_f$

$$f(t) = \begin{cases} 274t/t_1 + (5280/t_1)\, e^{-5485t} \\ \quad 0 < t \leqslant t_1 \\ 275.4\, e^{-80(t-t_1)} - 6598\, e^{-(5493t-80t_1)} \\ \quad t > t_1 \end{cases} \tag{13}$$

After 5 ms the exponentials in the second terms are negligible. Hence, for practical purposes $f(t)$ may be approximated as:

$$f(t) = \left\{ \begin{matrix} 274t/t_1 & 0 < t < t_1 \\ 275.4\, e^{-80(t-t_1)} & t > t_1 \end{matrix} \right\} = p(t) \tag{14}$$

TABLE 2

Peak kinematics of the human body model

Body segment	Weight (lb)	Rotation θ (deg)	Angular speed θ (deg/s)	Angular acceleration (deg/s)	Horizontal acceleration of link mass center (ft/s^2)
Torso	124.2	0.0	0.0	0.0	−22.2
Thigh	14.8	273.6	−4.89	291.1	−189
Lower leg	6.88	26.7	−7.12	245.1	−316
Foot	2.15	333.1	−9.35	275.3	−211

DISCUSSION AND APPLICATIONS

To validate the foregoing analysis, the kicking leg was modelled as a four-segment multilink system representing the torso, the thigh, the lower leg, and the foot, as in Fig. 4. The torso, which is not depicted in the figure, is assumed to move horizontally without rotation. Point O represents the hip joint and the thigh is assumed to rotate relative to the torso about O in a plane normal to the hip axis.

To use this model in validating the analysis a 148-lb subject was asked to use the knee-kicker while being filmed by a high-speed camera (100 frames/s). The segment accelerations were calculated by digitizing the film. Table 2 shows the results of the digitation of the time of impact. The table also lists approximate weights of the segments.

Using the data of Table 2, we can calculate the inertia force and hence, the applied force f on the knee:

$$f = \sum_{i=1}^{4} \omega_i a_i / g = 256 \text{ lb} \qquad (15)$$

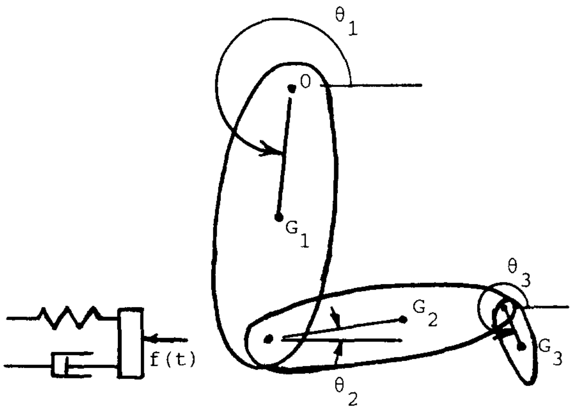

Fig. 4. Human body model.

where ω_i is the weight of segment i, a_i is the horizontal mass center acceleration of segment i, and g is the gravitational acceleration.

The difference between the results of eqns. (15) and (13) is about 6.5%. This is within the accuracy of the experimental measurements and the photography.

Next, observe in eqns. (13) and (14) that the force experienced at the knee is nearly equal to that transmitted to the force transducer and thus to the carpet. This means that the typical knee-kicker pad does little to attenuate the impulse. These results help explain the reported high level of knee injuries among carpet installers.

Finally, it is believed that the developed procedures and model can be used to evaluate new knee-kicker designs. Such designs would incorporate new pad materials which better absorb deleterious force transmissions. Indeed, such a pad would distribute the force experienced by the knee over a longer time while maintaining the sharp impulse applied to the carpet. Such designs are the subject of future research.

ACKNOWLEDGEMENT

Partial support for this research was provided by the National Institute of Occupational Safety and Health (NIOSH) under Contracts 85-35484 and 85-35521.

REFERENCES

Radin, E.L. and Paul, I.L., 1971. Response of joints to impact loading, I. In-vitro wear. Arthritis Rheum., 14(3): 356–362.

Tanaka, S., Smith, A.B., Halperin, W. and Jensen, R., 1982. Carpet layer's knee, N. Engl. J. Med., 307(20): 1277.

Bhattacharya, A., Mueller, M. and Putz-Anderson, V., 1985. Traumatogenic factors affecting the knees of carpet installers, Appl. Ergon., 16(4): 243–250.