THE BACK COMPRESSIVE FORCES DURING MAXIMAL
PUSH-PULL ACTIVITIES IN THE SAGITTAL PLANE

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Ten normal young male and ten normal young female subjects (each group with a mean age of 21.1 years) performed isometric and isokinetic (50 cm per second) push and pull activity at 35 cm, 100 cm and 150 cm heights. The subjects were placed on a specially designed subject-stabilizing-platform to stabilize their lower extremities. Horizontal push-pull forces were exerted through a friction-reduced rod and sleeve assembly attached to the modified Static Dynamic Strength Tester. The strength measured by a SM 500 load cell was fed to an IBM XT through an A to D converter. The postural records were made on a videotape. The posture and strength were synchronized through an external light signal. The strength for pull activities was higher than the corresponding push activities \( (p < 0.01) \). The isometric strengths were significantly higher than the isokinetic strengths \( (p < 0.01) \). Though the push strengths were significantly lower than the pull strength, the low-back compressive forces for the push activities were 129\% to 627\% of the corresponding pull conditions. It is concluded that the push activities are more hazardous due to the higher magnitude of compressive load and their faster contribution to the threshold level of cumulative load leading to the precipitation of injuries.

Despite frequent indulgence in push-pull activities on a shop floor as observed by Baril-Gingras and Lortie (1990), and considerable need of manual materials handling in industries push-pull still continues to be ill-investigated. Asfahal (1984) reported that for every ton of product manufactured 80 to 150 tons of materials are moved. In their observation of 29 workers performing 944 jobs, Baril-Gingras and Lortie (1990) found that nearly half of all material handling activities consisted of push-pull activities. Coupled with this information, the report by NIOSH (1981), Statistics Canada (1991) and Troup and Edwards (1985) that approximately 20\% of all back injuries which occur due to manual

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materials handling are due to push-pull activities in the United States, Canada and U.K. This makes push-pull activities of considerable industrial significance.

Low-back compression has been commonly accepted as an important risk factor in the causation of low-back injury in numerous epidemiological studies. A good citation and bibliography appears in NIOSH (1981), FRYMOYER and GORDON (1989) and POPE et al. (1991). KUMAR (1990) in a gender-, age-, body weight-, height-, occupational- and recreational activities-matched population found that cumulative load (lifetime exposure) was a consistent and significant risk factor among the institutional aides with back injury or back pain. None of the subjects in the “no pain” group of this study had reached the threshold range of cumulative load expressed in meganewton-years (MNY) of the subjects in the “pain” group. In view of the fact that the push-pull activities are commonly performed in many industries (such as shipping and receiving, moving companies, warehouses, department stores, supermarkets, agriculture and farming, retailing, policing, firefighting, laundry and many service sectors) it is logical to speculate that it will be one of the most common activities contributing towards accumulation of lifetime load. The fact that push-pull activities have been reported to be associated with 20% of injury precipitation may be misleading. Since the push-pull activities will require less force than the lift-lower activities of the same object, people would favor push-pull. Due to such frequency of these operations, they are likely to be a significant contributor to the cumulative load. A higher frequency of injury precipitation during lifting-lowering may be due to exceeding the tolerance limit in a single effort. The latter is more likely to happen during lifting-lowering as the compression generated during these activities is expected to be significantly higher than those of push-pull. Nonetheless, due to being favored activities, push-pull are thought to be contributing to this cumulative pool significantly.

The push-pull activities have been studied by several authors, but generally to establish strength capabilities of the experimental sample. Most of the studies reported in the literature are either based on static strength (KROEMER and ROBINSON, 1971; LAUBACH et al., 1972; MARTIN and CHAFFIN, 1972; AYOB and MCDANIEL, 1974; KROEMER, 1974; CHAFFIN et al., 1983) or an assessment of psychophysically maximal acceptable effort (SNOOK, 1978). DAVIS and STUBBS (1978) established maximum safe limits based on generation of 90mmHg intra-abdominal pressure. The dynamic strength measurements have been generally reported for one-handed efforts (GARG and BELLER, 1990; IMRAN and AYOB, 1990; MITAL and FAARD, 1990; IMRAN and RAMAKRISHNAN, 1992). KUMAR et al. (1991) reported two-handed static and dynamic strengths but did not report the associated low-back compressive forces. In a two-handed dynamic push-pull studies, LEE et al. (1989), ANDRES and CHAFFIN (1991), and GAGNON et al. (1992) applied biomechanical models for validation. However, a study looking at the effect of maximal push-pull activities on the back compressive forces will be of considerable value. If push-pull activities are favored by workers (BARIL-GINGRAS
and Lortie, 1990) and the cumulative load on the spine is an important risk factor in precipitation of the low back pain; it will be of strategic value to determine the pattern and magnitude of such compressive loads during these activities.

MATERIALS AND METHODS

Subjects. Ten normal young males and ten normal young females were volunteers for the study (Table 1). The subjects were free from any musculoskeletal or metabolic disorders. They had not suffered any injury of the upper extremity or the back over the last 12 months. The subjects were informed about the project and signed an informed consent form. The volunteering subjects were trained on the task before the experiment with submaximal exertion. On the day of experiment, suitably attired subjects were marked with circular sticky markers on tragus, shoulder joint, elbow epicondyle, wrist joint, knuckle, hip joint, knee joint, and ankle joint. Such prepared subjects were placed on the subject-stabilizing platform for the experiment.

Tasks. The subjects were required to perform a maximal two-handed push-pull exertion when instructed. They were trained to perform their exertions without jerk maintaining the direction of activity horizontal to the best of their ability in pulling. In pushing, when an extension bar was used, a guide sleeve fitted with ball bearing was rigidly fixed to maintain friction-reduced horizontal excursions. The isometric exertions were designed for a 5-s period, the first 2 s of which was taken in building the strength and the remaining 3 s were for maintaining at their peak strength. The isokinetic exertions were carried out at a single velocity of 50 cm/s displacement of the handle electronically controlled by the Static Dynamic Strength Tester (SDST). The first 5 cm of the displacement was used to build the strength and avoid the jerk. The rest of the displacement was carried out maintaining the maximal force. The isokinetic pulling was initiated with the arms fully extended while isokinetic pushing was started with the elbows fully flexed.

Table 1. Anthropometric data of experimental subjects.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Parameter</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Knuckle height (cm)</th>
<th>Knee height (cm)</th>
<th>Hip height (cm)</th>
<th>Shoulder height (cm)</th>
<th>Reach (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>Mean</td>
<td>21.1</td>
<td>173.0</td>
<td>61.2</td>
<td>77.0</td>
<td>53.1</td>
<td>92.3</td>
<td>143.0</td>
<td>64.2</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>2.5</td>
<td>6.4</td>
<td>9.4</td>
<td>4.2</td>
<td>2.8</td>
<td>3.2</td>
<td>6.1</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>25.0</td>
<td>179.0</td>
<td>62.6</td>
<td>80.2</td>
<td>58.0</td>
<td>98.5</td>
<td>149.0</td>
<td>68.3</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>18.0</td>
<td>157.0</td>
<td>48.7</td>
<td>66.4</td>
<td>48.4</td>
<td>87.0</td>
<td>127.8</td>
<td>57.0</td>
</tr>
<tr>
<td>Females</td>
<td>Mean</td>
<td>21.1</td>
<td>163.8</td>
<td>61.3</td>
<td>74.0</td>
<td>49.3</td>
<td>85.1</td>
<td>135.3</td>
<td>58.8</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>2.5</td>
<td>5.1</td>
<td>6.0</td>
<td>3.8</td>
<td>2.1</td>
<td>2.2</td>
<td>5.0</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>26.0</td>
<td>173.5</td>
<td>68.5</td>
<td>81.0</td>
<td>52.5</td>
<td>88.3</td>
<td>145.0</td>
<td>62.0</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>18.0</td>
<td>158.0</td>
<td>48.5</td>
<td>68.5</td>
<td>46.0</td>
<td>81.1</td>
<td>129.0</td>
<td>57.0</td>
</tr>
</tbody>
</table>
The subjects were informed that their maximal efforts were essential, but they will not be issued encouragement during the trial. However, immediately prior to every trial they were reminded and asked to exert their maximal effort. These sagittally symmetrical push-pull activities were performed at the heights of 35 cm, 100 cm and 150 cm. These heights were chosen to simulate the industrial working conditions at low, medium (hip) and high (above shoulder) levels from the floor. A total of 12 conditions (Figs. 1–3) (2 activities—push and pull × 2 modes—isometric and isokinetic × 3 heights—35 cm, 100 cm and 150 cm) were randomized. Each condition was tried three times with a minimum of 2 min rest between any two trials.

**Hardware.** The isometric and isokinetic push-pull strength was measured using a modified Static Dynamic Strength Tester (SDST) after KUMAR (1991) (Figs. 4 and 5). A description of the device follows. The Static and Dynamic Strength Tester provided a constant speed motion regardless of force applied to the handles. This speed could be adjusted by a velocity controller. The constant velocity was achieved by coupling the handle through a steel strap and one-way clutch to a shaft rotating at a fixed pre-set speed. The clutch uncoupled the mechanical resistance of the motor-driven system until the threshold speed was reached. This allowed resistance-free movement of the handlebar below the present...
speed. When the speed threshold was reached, the clutch engaged the constant-speed shaft and controlled the speed with a very high resistance. The strength tester consisted of the components: 1) Framework, 2) electromechanical drive, and 3) measuring system.

1) Framework. The framework (Fig. 4) consisted of a 100×100 cm platform raised by 35 cm. Two 200-cm-high vertical posts were affixed to the sides of the platform toward one end. The upper ends of these vertical posts were braced by a crossbar and additional vertical supports.

2) Electromechanical drive. The electromechanical drive (Fig. 5) consisted of an electronic speed control, a 0.25 HP d.c. motor (GE Model 5 BCD 56 CB 173) and a mechanical drive. The motor mounted on a worm gear was connected by a timing belt and a pulley system to a central rotating shaft. A strap drive drum was mounted on the constant speed drive shaft coupled through a pair of internal one-way sprague clutches (Fig. 5). A steel strap was wound around the strap drum at one end and attached to the load cell-mounted handle on the other. When a force was applied on the handlebar, it moved at a constant preset speed. An SCR electronic speed control was used to adjust and set the speed at which the drum could rotate. The Static and Dynamic Strength Tester permitted a controlled 0–150
cm per second displacement of the handlebar by adjusting the speed of the motor.

3) Measuring system. A displacement measuring potentiometer was used to measure the linear displacement. The velocity of the handlebar was measured by a tachometer coupled by a belt to the gearbox output. The tachometer signal was the input for the SCR feedback speed control. A load cell (Interface Model SM-500-500 lb) with a natural frequency of 1.5 kHz was inserted between the handlebar and the anchor. The output of the load cell was fed to a force monitor (ST-1, Prototype Design & Fabrication Company).

The modification consisted of an addition of a variable-height horizontal bar with a double roller in the middle separated by a gap of 0.5 mm. The space between the rollers allowed the passage of the steel strap of the SDST. By the variable adjustment, any height for the bar could be selected. A change from the push to the pull activity was achieved by simply flipping the steel strap by 180°. At the end of the steel strap, a load cell SM 500 was inserted between it and the handle 53 cm wide to simulate the size of an industrial carton. To maintain a fixed distance between the subject and the SDST due to a change in direction from pulling to pushing an extension bar of 53 cm guided through a sleeve fitted with a ball bearing (Fig. 6) was inserted during the exercise.
To achieve stabilization of the lower extremities of the subjects to eliminate variability of their contribution, a special stabilizing platform was built (Fig. 7). It consisted of a stable metal base and two uprights made of smooth cylindrical oil pipes. Three sliding padded and upholstered supports for the front of the legs and thighs travelled up and down on these uprights. The padded supports could be fixed at any position by a wingnut. A 6-cm-wide nylon strap was fitted to each of these padded supports with a car seat buckle. The latter allowed quick stabilization and release. This support platform was welded on two sleeves which slid on two horizontal metal tubes bolted to the ground by metal brackets. The support platform could be fixed at any point on the horizontal metal tubes to achieve the
desired distance between the SDST and the subject.

Data acquisition and analysis. The load cell of the SDST was fed to an IBM XT computer with Metrabyte DAS 20-A to D converter. The signals were sampled at 60 Hz. A special modular software was developed for data acquisition. The first module accepted the subject data and created a random sequence for the experimental conditions. The second module started the data acquisition, created files for data and saved the acquired data to those files. The third module instantly plotted the acquired data on the screen for quality control.

Each trial of each condition was videotaped for the entire trial using a VHS camera and video cassette recorder (VCR) at 60 frames per second. The trigger start of the data collection was marked on the videotape by a light flash in circuit in view of the camera. By using the internal clock of the computer and frame count of the videotape, the force and posture were synchronized. The postural data at the
Fig. 6. Extension bar assembly with ball-bearing sleeve for pushing activity.

Fig. 7. Subject stabilizing platform.
peak force exertion were extracted from the videotape. These consist of the wrist angle, the elbow angle, the shoulder angle, the hip angle, the knee angle and the ankle angle (Fig. 8). The angles were measured from the pictures printed on photographic paper by the Video Printer P 60. The postural data and the force data from the load cell were inputted into the biomechanical models (CHENG and KUMAR, 1991) to calculate the back compressive forces. The details of the model are summarized in Appendix 1. The descriptive statistics and the analyses of variance for the push-pull strength and the low-back compressive forces were calculated.

RESULTS

The mean peak and the average push-pull strengths recorded from the male and the female experimental samples are presented in Figs. 9 and 10, and 11 and 12, respectively. The pulling strengths, both peaks as well as averages, were always greater than their corresponding pushing strengths ($p < 0.01$) except at low height in isokinetic condition among males. The highest strength was recorded during the medium height isometric pull in both sexes. The isokinetic strength values were always significantly lower than the isometric strengths ($p < 0.01$). Similarly, the males were 10% to 40% stronger than the females ($p < 0.01$). Also, the height at
Fig. 9. Isometric push-pull strength of the males.

Fig. 10. Isokinetic push-pull strength of the males.

Fig. 11. Isometric push-pull strength of the females.
which these activities were performed had a significant effect on the push-pull strength ($p < 0.01$). The medium height was always associated with highest strength generation.

The means and standard deviations of the moment arm, the external moment and the back compressive force for the males and the females are presented in Tables 2 and 3, respectively. While the strength generated between the corresponding isometric and isokinetic conditions were significantly different, the external moments were not. However, the strength generated as well as the external moments for the corresponding heights in the same mode for push and pull were significantly different ($p < 0.01$) (Tables 2 and 3). Under isometric conditions, the

![Fig. 12. Isokinetic push-pull strength of the females.](image)

Table 2. Moment arm, external moment and back compression force among males during push-pull exertions.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Moment arm (cm)</th>
<th>External moment (N·m)</th>
<th>Back compression (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Isometric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>47.7</td>
<td>6.6</td>
<td>154</td>
</tr>
<tr>
<td>Medium</td>
<td>49.9</td>
<td>6.7</td>
<td>244</td>
</tr>
<tr>
<td>High</td>
<td>53.3</td>
<td>5.9</td>
<td>253</td>
</tr>
<tr>
<td>Pull</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>50.0</td>
<td>8.0</td>
<td>166</td>
</tr>
<tr>
<td>Medium</td>
<td>44.6</td>
<td>8.1</td>
<td>319</td>
</tr>
<tr>
<td>High</td>
<td>43.7</td>
<td>10.4</td>
<td>281</td>
</tr>
<tr>
<td>Isokinetic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>54.9</td>
<td>5.9</td>
<td>161</td>
</tr>
<tr>
<td>Medium</td>
<td>61.6</td>
<td>7.7</td>
<td>265</td>
</tr>
<tr>
<td>High</td>
<td>64.4</td>
<td>6.4</td>
<td>248</td>
</tr>
<tr>
<td>Pull</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>36.8</td>
<td>5.8</td>
<td>118</td>
</tr>
<tr>
<td>Medium</td>
<td>38.0</td>
<td>7.6</td>
<td>204</td>
</tr>
<tr>
<td>High</td>
<td>33.4</td>
<td>6.8</td>
<td>151</td>
</tr>
</tbody>
</table>
Table 3. Moment arm, external moment and back compression force among females during push-pull exertions.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Moment arm (cm)</th>
<th>External moment (N·m)</th>
<th>Back compression (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Isometric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push Low</td>
<td>44.1</td>
<td>2.3</td>
<td>109</td>
</tr>
<tr>
<td>Medium</td>
<td>46.6</td>
<td>3.9</td>
<td>174</td>
</tr>
<tr>
<td>High</td>
<td>44.9</td>
<td>10.2</td>
<td>149</td>
</tr>
<tr>
<td>Pull Low</td>
<td>45.7</td>
<td>3.0</td>
<td>134</td>
</tr>
<tr>
<td>Medium</td>
<td>46.1</td>
<td>4.0</td>
<td>268</td>
</tr>
<tr>
<td>High</td>
<td>45.2</td>
<td>3.7</td>
<td>185</td>
</tr>
<tr>
<td>Isokinetic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push Low</td>
<td>52.6</td>
<td>4.6</td>
<td>95</td>
</tr>
<tr>
<td>Medium</td>
<td>56.0</td>
<td>8.0</td>
<td>167</td>
</tr>
<tr>
<td>High</td>
<td>57.0</td>
<td>11.2</td>
<td>145</td>
</tr>
<tr>
<td>Pull Low</td>
<td>43.3</td>
<td>1.9</td>
<td>106</td>
</tr>
<tr>
<td>Medium</td>
<td>34.3</td>
<td>4.6</td>
<td>144</td>
</tr>
<tr>
<td>High</td>
<td>37.9</td>
<td>4.5</td>
<td>120</td>
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Pushing-pulling are common activities of everyday life in addition to being frequent industrial practices. BARIL-GINGRAS and LORTIE (1990) have reported that the workers favor push-pull to lift-lower. The industrial surroundings in which such activities are performed vary from job to job and also from site to site. Therefore, determination of the maximal capability in an optimum, unrestricted or carefully designed setting to provide the maximal mechanical advantage to the body.
system may yield results with potential for overexertion. Since the push-pull activities involve the upper extremity and the trunk with or without the need or possibility of the lower limb involvement, it will be of considerable ergonomic significance to standardize the role of the lower extremities in such measurements. Therefore, the results reported in this study reflect more accurately the push-pull capabilities of the back-arm aggregate in the sagittal plane at low, medium and high heights.

In addition to many pushing-pulling efforts in the horizontal plane, the work places frequently involve such activities at various angles. Depending on the configuration of the surroundings and forces, the resolution of forces may or may not assist the task. The latter, again, creates a nonstandard situation. Any task performed under these circumstances, then, if not related to standards developed to simulate the tasks, can not be used for comparisons among studies. It is therefore, of value to do the testing with horizontal force application. Such a configuration will ensure a push-pull force which will be totally transmitted as such. In the current study, a conscious effort to exert in horizontal direction during pushing and pulling through a “ball bearing-fitted” guiding sleeve maintained the direction of force exertion as close to the horizontal as possible. The variations observed in these efforts may reflect the true posture-dependent arm-back aggregate capability. It is, therefore, argued that the results obtained in this study are the most valid and appropriate measures of capability which take into account posture and height of exertion. It is also contended here that any effect of the mode on the push-pull capability and the resulting musculoskeletal stress will be more reliably and validly reflected.

The peak strengths produced were significantly affected by the height at which these were exerted. The medium height invariably produced maximal strength for both males and females in the isometric and isokinetic modes in both push and pull. This height made it possible to take maximal advantage of the posture. The strength produced was also reflected in the external moment which was also greatest at the medium height. The pull activities invariably generated highest strength and were significantly higher than the push strengths \((p < 0.01)\). The isometric push moment among the males for the low, medium and high heights were 92\%, 76\% and 90\% of the corresponding pull moment. However, the back compressive forces for the same conditions for the push activities were 330\%, 207\% and 136\% greater than those of the corresponding pull activities. In the isokinetic conditions among the males, the peak push strengths were significantly lower than the peak pull strengths \((p < 0.01)\). Nonetheless, the peak external moment for the push activities at the low, medium and high heights were 136\%, 130\% and 164\% of their corresponding pull conditions. The back compressive forces for the isokinetic push conditions at the low and medium heights were 331\% and 402\% of their corresponding pull conditions. Among the females, the isometric push conditions at the low, medium and high heights the peak external
moments were 81%, 64% and 80%; and the back compressive forces were 446%, 347% and 390% of their corresponding pull conditions, respectively. Similarly, for the isokinetic conditions the peak external moments at the low, medium and high heights were 89%, 116% and 120%; and the peak back compressive forces were 627%, 177% and 129% of their corresponding pull conditions.

The findings of this study clearly demonstrate that, although one is capable of exerting far less force in pushing, it is associated with disproportionately high level of back compressive forces. Thus, not only one can produce less force but generate considerably higher compression during pushing, significantly accentuating the chances of traumatic injuries. Besides, the cumulative load or lifetime exposure to compression has been shown to be an important risk factor (KUMAR, 1990). The disc compression generated during isometric pushing activities in both sexes ranged between 200% to 400%, except at shoulder height among males which was 140% (Tables 2 and 3). In isokinetic efforts the lumbosacral compression forces during pushing activities ranged from 130% to 630% greater than those which occurred in pulling activities with the exception of the 150-cm height among males (Tables 2 and 3). Thus, the accumulation of the compression load exposure by indulgence in the push activities can grow several hundred percent faster compared to the pull activities. It is, therefore, proposed that the push activities in industry must be considerably reduced immediately and be planned to be eliminated in the long term.

REFERENCES


APPENDIX 1

The Biomechanical Model

A. Calculation of Joint Intersegmental Resultant Forces and Moments

At any instant during the course of motion, every segment of the human body is subjected to forces and moments which maintain the state of equilibrium. The equations used in the calculation of the intersegmental resultant forces and moments were as follows:

Force equations at nodal joint $n$:

$$F_x(n) = F_x(n-1)L_x(n)$$

$$F_y(n) = F_y(n-1) + W_y(n-1) + L_y(n)$$

$$F_z(n) = F_z(n-1) + L_z(n)$$

where $F_x(n)$, $F_y(n)$, and $F_z(n)$ are intersegmental resultant force components at joint $n$; $L_x(n)$, $L_y(n)$, and $L_z(n)$ are the external load components acting on the joint $n$; the $W_y(n-1)$ is the weight of segment $n-1$.

Moment equations at nodal joint $n$:

$$M_x(n) = M_x(n-1) + A_y(n-1) \times F_z(n-1) - A_z(n-1) \times F_y(n-1)$$

$$M_y(n) = M_y(n-1) + A_z(n-1) \times F_x(n-1) - A_x(n-1) \times F_z(n-1)$$
\[ M_z(n) = M_z(n-1) + A_x(n-1) \times F_y(n-1) - A_y(n-1) \times F_x(n-1) \]
\[ + A_x(n-1) \times W_y(n-1) \]  
\[(6)\]

where \( M_x(n) \), \( M_y(n) \), and \( M_z(n) \) are intersegmental resultant moment components at joint \( n \); \( A_x(n-1) \), \( A_y(n-1) \), and \( A_z(n-1) \) are moment arm components at the joint \( n \). Subsequent calculations were similarly performed.

Thus, at any instant, equations (1) through (6) were applied to each body segment. Since the moment arms, vector of links, and external loads of moments acting on each body segment were computed from the equations of equilibrium. The forces and moments consisted of the following components: the weight of the body segment and the external load, the resultant forces; and the moments at the joint center. A cutting plane was chosen from a specific spinal joint level to distribute the intersegmental resultant forces and moments into disc compressive forces.

B. Calculation of Muscle and Disc Forces

The calculation procedure first used a linear optimization technique (SIMPLEX) which minimized the compressive force at one disc joint (e.g. L5/S1) with three moment equation constraints and muscle stress upper limits to solve the muscle force distributions. These solved muscle forces were then substituted into three force equilibrium equations to solve the disc compressive and shear forces at all 6 disc joint levels.

The optimization cost function and criterion is defined as follows: find \( F_{mi}(j,k) \) (6 muscles), of design variables that minimized the cost function (the disc compressive force). In the \( y \)-component force equilibrium equation (equation 7) the summation of the disc compressive force (a negative component in the system) and six \( y \)-component muscle forces is achieved. This is considered equal to the \( y \)-component intersegmental resultant force at the specified disc level (e.g. L5/S1). Since the \( y \)-component intersegmental resultant force is a constant, to minimize the disc compressive force is the same as minimizing the summation of the six \( y \)-component muscle forces as shown in equation 8.

\[ \sum_{i=1}^{6} F_{mi}(j,k) - F_c(j,k) = F_r(j,k) \]  
\[ -F_c(j,k) = F_r(j,k) = \sum_{i=1}^{6} F_{mi}(j,k) \]  
\[(7)\]
\[(8)\]

Cost Function: \( \min \sum_{i=1}^{6} F_{mi}(j,k), \) 

where \( J = 2 \), \( y \)-component; \( k = 4 \), L5/S1 joint level

Subject to:
(1) equality constraints:
\[ \sum_{i=1}^{6} (F_{mi}(j,k) \times R_{mi}(j,k)) = M_r(j,k) \]  
\[(9)\]
\( j = 1, 2, 3 \)
\( k = 4 \), L5/S1 joint level

where \( F_{mi}(j,k) \) and \( R_{mi}(j,k) \) are the muscle force components and corresponding moment arms in the \( j \)-direction of the \( i \)-th muscle at the \( k \)-th joint level, \( M_r(j,k) \) are the intersegmental resultant moments in the \( j \)-direction of the \( k \)-th joint level.

(2) explicit bounds of design variables:
\[ F_{mi}(j,k) A_{mi}(j,k) \leq f_u \text{ (e.g., 100 N/cm²)} \]  
\[(10)\]
where \( Am_i(j, k) \) are the muscles' physiological cross-sectional area and \( f_u \) is the upper limit of the muscle stresses.

This linear programming problem was solved to determine optimal muscle tensile forces which minimize the disc compressive force on the spine. The disc joint forces in each joint level were then calculated from equations of force equilibrium.

\[
\sum_{i=1}^{6} Fm_i(j, k) - Fc(j, k) = Fr(j, k)
\]  

(11)

SIMPLEX algorithm was used in solving this linear optimization problem. The convergence parameter was set up to 0.0001.