TOWARDS IMPROVED INFANT RESTRAINT SYSTEM REQUIREMENTS

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ABSTRACT

Observational surveys and analysis of motor vehicle collision data files have confirmed that some infants are transferred to the next category of restraint or taken out before they have "out-grown" their prescribed protective devices. Legislation, enforcement and education countermeasures are tools that have been used to increase proper restraint use among infants. The next phase of improving protection for infants is regulating aspects of the product to increase prolong proper use. The introduction of larger infant dummies in sled testing is one of the most important of these regulatory initiatives as it applies to infant restraints.

Canadian collision data files were analyzed and crash tests simulations (sled tests) were conducted. Convertible restraints were tested in the rear and forward facing configurations using 6-, 9-, 12- and 18-month and 3-year dummies. All parameters for the 12- and 18-month dummies were recorded for a more in-depth comparison of the performance of restraints when tested facing forward or rearward. Every convertible restraint tested in the rear facing configuration passed the CMVSS 213.1/FMVSS 213 criteria with the 6-, 9-, 12- and 18-month dummies. Some of the restraints passed the regulations' criteria with the 3-year old dummy although the dummy's legs interaction with the standard seat back was a challenge for proper installation. In all cases, the structural integrity of the restraint was intact.

Canadian child restraint use surveys were reviewed to determine the level of proper use and orientation of infant restraints. Likewise, accident data files were analyzed to determine the proportion of infants and children involved in motor vehicle collisions who occupy infant/child restraint devices. The injury severity levels were determined. These injuries were compared for restrained/unrestrained and ages of occupants, and if the restraint devices was used properly or not.

Analytical methods are employed to determine whether any significant effects on the restraint performance exist due to infant dummy size, restraint model or the interaction of the two. Also, similarities and differences in performance among the forward and rear facing configurations and various restraint models are measured and compared.

Infants and young toddlers, are provided with a higher level of safety when restrained in a rear facing infant restraint system as long as possible rather than not being restrained, being restrained in a forward facing restraint or restrained by a seat belt.

INTRODUCTION

In some countries it has long been recognized that restraining children in devices facing the rear of the vehicle offers optimum protection and a high degree of acceptability by users.[1 2 3 4 5] In other countries the use of restraints that face the rear of the vehicle have been met with mixed reactions by the users.[6] In Canada, currently close to 26 % of users of infant restraints designed to face the rear orient them in the wrong direction.[7] Because of snowy and wet weather conditions during the Canadian winter, it is anticipated that, at first, acceptance of rear facing restraints for older children may be limited to pre-walkers. However, with 50 % of one-year old children not yet walking[8] greater use of rear facing restraints for older infants would be anticipated over the years.

The heavy head of children in comparison to their total body mass[9] and their weak neck is best protected while being in a rear facing restraint by the continuous seat back. This is especially important in frontal collisions, the most frequent and severe direction of impact encountered in automotive crashes. In Canada, victims of frontal impacts account for 44 % of all collision victims[10]

Rear facing infant restraint systems have been available in North-America since the late-sixties.[11] A Canadian regulation governs their safety performance since 1972.[12] Recognizing the specific needs of infants, a regulation addressing the safety of rear facing infants was promulgated in Canada in 1982.[13] The main objective o this regulation is to ensure the safety of new-borns, while properly restrained in a rear facing device, until they weigh 9 kg. At the time the regulation came into force, the only available dummy to test such a device was the 50th percentile 6-month "bean bag" dummy.[14] The mass of this and other dummies used for testing in this program are listed in Table 1. In 1996 the use of the 9-month (3/4 TNO) dummy[15] was permitted in Canada.[16] This permitted the maximum usable mass for rear facing infant restraints to be increased to 10 kg.

Table 1.
Mass of dummies used in this test program

50th percentile dummies	mass (kg)	mass (lb.)
6- months	7.8	17.2
9- months	9	19.8
12- months	10.0	22.0
18- months	11.5	25.4
3- years	15.73	34.69

One of the dynamic criteria for rear facing infant restraints in Canada is that the head of the dummy does not pass a pair of orthogonal planes at the top-most part of the restraint at any time during the crash simulation. These planes are illustrated in Figure 1. The other criteria is that the angle of the seat back of the infant restraint with respect to the horizontal does not exceed 70 degrees from the vertical. This is graphically depicted in Figure 2.

The next category of restraints in Canada are designed to protect children whose mass is over 9 kg and less than 22 kg. The Hybrid II 3-year old[17] is the referenced surrogate to test these restraints in accordance with the regulation.[18] The criterion established for the simulated dynamic crash test is that at no time during the test should any part of the head of the dummy exceed a distance of 720 mm from a fixed reference point on the standard seat.[19] This criterion and the dummy with which the test is perform is equally applicable for forward facing or rear facing restraint systems for older children. Because the head of a 3-year old dummy in current convertible restraint designs is already beyond the permissible 720 mm limit, rear facing child restraints have not been sold in Canada.

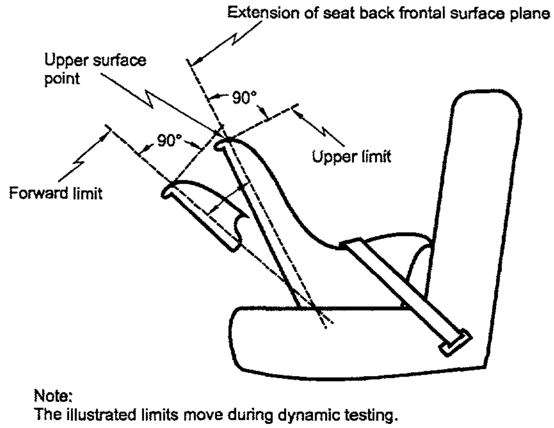

Figure 1. Orthogonal planes limiting the movement of the head of the dummy during dynamic testing.

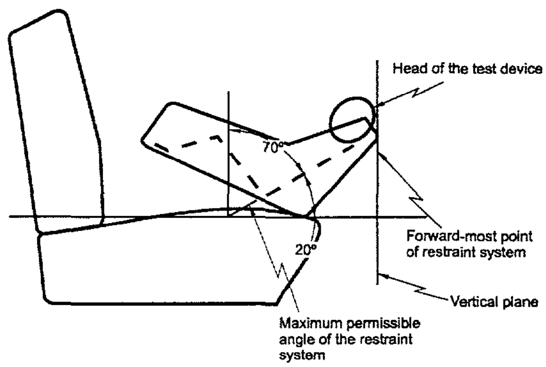

Figure 2. Maximum permissible seat back tip angle during dynamic testing

Regnonizing the benefits of protecting children in a rear facing orientation, consideration was given to solutions that would allow Canadian restraint users a safer alternative.[20] A test program was conducted using different makes of convertible restraint systems. A convertible restraint is one that is used in a reclined position and installed facing the rear of the vehicle for infants. The convertible restraint is then turned to face the front of the vehicle in a more upright position to restrain older children.

Convertible restraints of the same make and model were tested forward facing and rear facing. The head and chest accelerations, neck forces and moments and shoulder loads were compared for the forward and rear facing modes under experimentally controlled conditions. A comparison was made with previously reported data[21] of the forward configuration when the restraints were untethered.

It was expected that the head and chest accelerations, neck forces and moments would tend to have lower values in the rear facing configurations as compared to forward facing. No references on shoulder loads and threshold could be found in the literature. Only relative effects on shoulder loads could be analyzed. However, it was predicted that F_z would increase in the rear facing configuration as compared to forward facing, while F_x would decrease.

The testing was performed using some older generation dummies, the 6-month "bean bag" and the 3-year old Hybrid II dummies; one newer but uninstrumented 9-month (TNO ¾) and two state-of-the-art fully instrumented 12- and 18-month CRABI dummies.[22 23] These dummies were selected since they surrogate children of physical development that most likely benefit from using rear facing restraint systems. The capacity of the CRABI dummies to measure upper and lower forces and triaxial moments in the neck allowed for the recording of new parameters. A literature search has not identified any studies measuring neck upper and lower forces and triaxial moments using these dummies in child restraints with tethers.

Four commercially available convertible restraint systems and the CanFIX[24 25] were tested. All restraints tested had a similar T-shield type harness design system to minimize harness variability. T-shields are typical and commonly used in Canada.

The make of child restraint system was not expected to have any significant effects on the results within the parameters recorded. The performance of the CanFIX was expected to be slightly better relative to similar child restraint systems since the base was rigidly attached to the standard bench seat of the sled.

A major analytic objective of this research study was to determine whether any significant differences in performance among the infant restraint systems exist, particularly as these differences relate to any significant effects due to infant restraint type, dummy size and particularly restraint installation orientation (i.e., forward-facing or rear-facing).

Canadian field accident data were also analyzed to determine the crash involvement of restrained children, properly and improperly restrained, by injury severity.

ANALYSIS OF CANADIAN COLLISION DATA FILES

Data Source

Detailed national investigation data – known as 'Level II accident investigation case studies' – were analyzed in an attempt to shed some light on the nature of the child's restraint status and their injury severity. Level II accident investigations differ from Level I (police investigated and reported) in that they are Level II accident investigations differ from Level I investigations (police investigated and reported) in that they are conducted by specially trained accident investigators and reconstructionists and the breadth, detail and accuracy of information collected on the factors and characteristics present in the collision is significantly greater. Specifically, the Level II Accident Investigation Passenger Car Study (PCS) [26] that was used is an in-depth investigation of motor vehicle collisions in which at least one passenger car is involved and at least one occupant of the vehicles involved was either killed (fatal collision investigations) or injured (injury-producing collision investigations). The entire database contains 363 data elements (categorized within 27 separate files - each file represents a specific type of data collection form, e.g. vehicle, restraint use). An extensive range of collision, road user, road/infrastructure, vehicle, environment and temporal factors and characteristics associated with each accident investigation case study are described. The number of case studies in the databases totals 7,853. The survey was conducted between 1984 and 1992 inclusive by Transport Canada and a national network of ten university-based accident investigation teams located within eight provinces including British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, New Brunswick and Nova Scotia. A statistically representative survey design and sampling plan was designed by Transport Canada (and implemented by the accident investigation teams) to ensure 'random' and 'unbiased' selection of collisions for investigation. Due to financial limitations it was not possible to obtain sufficient personnel resources to conduct the survey on the entire road system networks in each province. As a result the geographic coverage of the survey was restricted to roads and highways that were within a 80 km radius of the university at which the accident investigation team is located.

These data bases were analyzed employing the methods and procedures developed by Stewart[27] to identify injury severity of children in fatal and injury producing collisions cross-classified by correctness of restraint installation, correctness of restraint system use, and the age of the child (six age groups were analyzed including 0-6 months, 6-9 months, 9-12 months, 12-18 months, 18-36 months and 36 to 60 months). Unfortunately, due to the detailed level of this information coupled with the relatively small number of case studies completed across Canada each year, the final cross-classified data base quickly reduces to only 129 children meeting the analysis criteria above. Therefore, all estimators reported here are subject to high variability, i.e., the errors associated with them are quite large - in the order of 40 % and higher in some instances.

Results of PCS Analysis

Among the 129 injured children in the PCS data files between the years 1984 to 1992 there are 41 fatalities and 88 injuries. A fatality is defined as any child who died within 30 days of injuries sustained in the motor vehicle collision. An injury is defined as visible signs of being hurt and an injury form being completed for the individual.

Examination of the results for the fatally injured children showed that for the age groups 0-6 months and 6-9 months all the children killed were in infant restraint systems that were both incorrectly installed and improperly used (i.e., the child was not properly restrained in the infant restraint seat). For the 12-18 month age group the results indicate that: 32.7 % of the fatally injured children were in a child restraint system that was improperly installed and improperly used; 36.6 % of the deceased children were in a child restraint system that was incorrectly installed, but the child was properly restrained in the system itself; and 30.6 % of this fatally injured age group were in child restraint systems that were correctly installed and properly used. The other age groups analyzed, namely 9-12 months, 18-36 months and 36-60 months were not represented in the fatally injured case studies over the years 1984 to 1992 inclusive.

A similar analysis of the children injured in the PCS data bases revealed that all of the 0-6 month old children injured in a collision accommodated infant restraint systems that were not correctly installed and who were not properly restrained in the infant restraint system itself. Among the 6-9 month old infants, 50 % of the injured children were improperly restrained in an infant seat that was also incorrectly installed. The other 50 % of these injured 6-9 month old infants were properly restrained in a system that was correctly installed as well. The analysis of the 9-12 month old infants showed that 92.2 % of the infants injured in collisions were improperly restrained in a system that was also incorrectly installed. The remaining 7.8 % of the injured infants were properly restrained in the restraint system itself, but unfortunately the restraint system was incorrectly installed in the vehicle. The other three age groups (12-18 months, 18-36 months and 36-60 months) were not represented in the injured PCS data bases.

Summary

Although it must be re-iterated that the results provided above are subject to high levels of error (due to the small sample sizes they comprise within the entire PCS data bases) the trend is quite evident.

A strong correlation between incorrect restraint installation, improper restraint use and the probability of sustaining an injury or fatality is quite apparent. It is therefore necessary to work towards improving protection for infants through mechanisms such as regulating aspects of the various restraint system products to increase both their correct installation and proper use.

SLED TEST METHODOLOGY

Test Set-Up

Laboratory tests were conducted on the HyGe sled at the Defence and Civil Institute of Environmental Medicine (DCIEM) at a δV of 48 km/hr. The pulse was 20 "g" for a duration varying between 11 and 48 milliseconds. The standard bench seat was in accordance with drawing package NHTSA SAS-100-1000. These conditions, specifications for atmospheric soaking and test preparation, are specified in Canadian test procedures for testing child restraint systems.[28] Contrary to European practice,[29] this test program was not conducted with a simulated dash, rather the restraints were allowed to travel forward uninterrupted. As opposed to Australia[30], rear facing restraints are not yet used in Canada with a tether. Therefore the rear facing tests have been performed without a tether whereas the forward facing restraints were tethered.

High-speed cameras were mounted on the test sled such that the films could be analyzed to determine dummy motion and maximum excursion.

Dummies

CRABI 12-month and 18-month fully instrumented anthropometric test devices were used in this test program. These dummies represent occupants in the targeted ages for increasing the maximum occupant mass in Canada. To compare with the current typical use and test methods, a "bean bag" 6-month and an un-instrumented 9-month old (TNO ¾) dummies were used. Finally, to assess the potential of reviewing the criteria for a larger mannequin to be used for rear facing testing, a Hybrid II 3-year instrumented with head and chest acceleration sensors was also used.

Both CRABI dummies were fully instrumented with sensors as summarized in Table 2.[31] These included force and moment transducers for the upper and lower neck and shoulder loads. The dummies were clothed as specified in the current test method[32] for child restraint systems with adjustments made for their respective sizes.

Table 2.
CRABI 12- and 18-month instrumentation

LOCATION	TYPE	AXIS	FULL SCALE	OUTPUT @ CAPACITY
Right/left shoulders	Denton model 2791	F_X	1 780 N	1.5 mV/V
		F_Z	1 780 N	1.5 mV/V
Upper and lower neck	Endevco model 7264-2000	F_X	890 N	1.8 mV/V
		F_Y	890 N	1.8 mV/V
		F_Z	2 225 N	0.8 mV/V
		M_X	56,5 N-m	2.5 mV/V
		M_Y	56,5 N-m	2.5 mV/V
		M_Z	33,9 N-m	1.3 mV/V
Head	Endevco 7264 A-2000	a_X	200 g	1.4 mV/V
		a_Y	200 g	1.4 mV/V
		a_Z	200 g	1.4 mV/V
Thorax	Endevco 7264 A-2000	a_X	200 g	1.4 mV/V
		a_Y	200 g	1.4 mV/V
		a_Z	200 g	1.4 mV/V

Only the CRABI 18-month dummy was available to test the CanFIX.

Restraints

Four restraints commercially available in Canada and the CanFIX concept restraint were selected for the tests. All restraints tested including the CanFIX had a similar T-shield type harness design system to minimize harness variability. The commercial restraints have not been identified in the paper by make and model but rather by letter codes, "T", "S", "C' and "U".

A new restraint was used for every test. The dummy was placed in the restraint according to the procedures recognized in the field.[33 34] Similarly, every restraint was installed on the standard seat according to prescribed procedures of CMVSS/FMVSS (in references).

<u>Repeatability Tests</u> - Repeatability testing was performed within five different test conditions. Two tests were performed for each of the eight configurations. This information is reported in Table 3.

Table 3.
Repeatability Tests List

Restraint	Run Numbers	Repeatability Runs
"T"	2525 & 2566 2524 & 2537 2631 & 2632 2600 & 2607	√
"S"	2536 & 2570	√
"U"		no
"C"		no
CanFIX		no

<u>Forward vs. Rear Facing Performance</u> - As one of the objectives of this study is to determine the effect of restraining children rear facing as opposed to forward facing, every restraint in the test program was tested in both configurations with every one of the dummies.

<u>Corrected Neck Values</u> - The values recorded for upper and lower neck moments M_y' have been corrected to take into account the off-centre location of the sensors

in the upper and lower neck of the CRABI 12- and 18-month old dummies.[35]

$$M_y' = M_y - 0.0058\, F_x \qquad (1.)$$

where M_y' is the corrected neck moment about the Y-axis
M_y is the recorded neck moment about the Y-axis
F_x is the recorded neck force along the X-axis

The neck moment values are reported in the corrected format.

Film and Analysis - Each test was recorded and the data were analyzed using the following equipment :

- Transducers on the sled were supplied with 10 V. DC from local sled-mounted power supplies. Outputs were fed to a sled-mounted, variable gain and offset amplifiers which converted the signals from differential to single-ended.
- Amplified signals were sent to active analog filters (via a low-noise multi-coaxial umbilical cable) which filters at SAE classes 180, 600 or 1000 Hz depending on the rate at which the signals were sampled (1500, 5000, or 8000 samples/sec).
- Filtered outputs were fed to a series of four National Instruments NB-MIO-16 multifunction boards containing 12-bit A/D converters which provided direct memory access to the RAM of a Macintosh II FX.
- Data were then transferred to disk, where custom-designed National Instruments Labview software was used to provide for digital filtering (at SAE class 60, 180, 600, or 1000 Hz),[36] and for scaling, further processing and plotting.

The video recordings were used to perform the kinematics analysis for each test and determine maximum head excursion. This information was recorded using:

- A Kodak EM Ektapro Motion Analyzer system.
- A Kodak High-gain imager (video camera).
- A Kodak EM Processor (model 1012) producing black & white motion pictures with X-Y electronic crosshair calculation capability.
- The frame rate was 500 frames per second.
- The shutter speed was 1/1000 sec.

RESULTS

The numeric results for every test in the program are listed in Appendix A, Table A-1. For the purposes of this paper, maximum values for head and chest excursion, chest acceleration, upper and lower neck F_x and F_z and corrected M_y and right and left shoulder loads are reported for the 12- and 18-month old mannequins. Original restraint back angle and maximum seat back angle with respect to the vertical are reported for the non-instrumented mannequins (6- and 9-month old and 3-year old).

The results are graphically presented in the Appendix "B" as Figures B-1 through B-12.

The acceptable limits for head excursion of 720 mm and chest acceleration of 60 g are those specified in CMVSS 213. For reference purposes, the 80 g acceptable level of head acceleration was adopted from the criteria for the 3-year old dummy level for built-in child restraint systems.[37]

Crash reconstructions have led researchers to establish injury threshold limits for the upper neck of different dummies.[38 39 40] Since the 12- and 18-month dummies used in the current study are relatively new, a literature search has not produced any studies that have established threshold levels for their neck. In such cases for the purpose of this analysis, thresholds from all previous studies have been included where appropriate in the graphs of Appendix "B". Table 4 summarizes the threshold values of previous studies.

Table 4.
Threshold limits - upper neck - studies

Researcher	Dummy used for reconstruction	Tensile axial force F_z (N)	Shear force F_x (N)	Forward bending moment M_y (N-m)
Planath et al., 1992	3-year old	1000	300	30
Trosseille and Tarrière, 1993	six-month old CRABI	1200	950	41
Janssen et al., 1993	9-month - adult Hybrid III values /scaling	850	800	41

For comparative purposes, whenever a threshold is associated with a parameter, a line is drawn at the threshold level in the graphs.

Effect Dummy Size on Seat Back Tip Angle

The initial seat back angle was, as expected, not greatly influenced by the size of the dummy. Restraint "C" demonstrated a difference where the initial angle increased with the size of the dummy because of leg interference with the seat back of the standard seat.

The maximum seat back angle has a tendency to increase as the size of the dummy increases. This was expected since a heavier dummy applies more load during the test on the seat back. This trend was not consistent with Restraint "C" but could be attributable to dummy leg interference with the standard seat back as described above.

In all cases the convertible restraint tested with larger dummies than specified in the current Canadian regulation passed the maximum seat back angle in the rear facing configuration.

The structural integrity of the restraints was not damaged during the test.

Effect of 12- Versus 18-Month Dummy

The following analysis is based on the more exhaustive data recorded using the 12- and 18- CRABI dummies.

Head Acceleration - The head acceleration data is presented graphically in Appendix "B", Figure B-1. In all cases the head acceleration is between 30 and 59 % lower than the accepted threshold of 80 g's. In every case, but Restraint "S" and Restraint "T" and the CanFIX tested with the 18-month dummy , the head acceleration was either lower or approximately equal, for rear facing compared to forward facing. In the absence of a simulated seat back or dash, all the head accelerations were inertial.

Chest Acceleration - Figure B-2 of Appendix "B" presents the results for chest acceleration recorded during this test program. In all cases, the chest acceleration was lower when a similar restraint was tested with the same dummy and placed rear facing as compared to forward facing. In all the cases tested, the chest acceleration was lower than the accepted threshold for child restraints.

Upper Neck Loads **(F_x and F_z)** - The data for upper neck loads F_x and F_z are presented respectively in figures B-3 and B-4 of Appendix "B". The lack of head contact with any external object and the similar restraining forces mean that the head would be restrained by the neck alone. In all cases, the upper neck load x-component, F_x was always lower for the rear facing than for the forward facing configuration. The rear facing values for F_x for Restraint "S", Restraint "U" tested with the 18-month and the CanFIX exceeded the threshold suggested by one study, whereas F_x exceeded the same threshold for every forward facing configurations.

For F_z in every case, but Restraint "T" tested with the 18-month and the CanFIX, the result was lower for the rear facing than the forward facing configuration. In fact for three of the eight tests with the commercial restraints, the forward facing value exceed the three thresholds suggested by various studies. None of the restraint in the rear facing installation exceeded the three thresholds with the exception of the CanFIX.

Upper Neck Moments (M_y) - Upper neck moments about the y-axis, M_y are reported in Figure B-5 of Appendix "B". In half of the test conditions, upper neck M_y was lower rear facing than forward facing. In the other half however the reverse was true. No definite trend could be identified from the data and more investigation may be required to be more conclusive. However, in all forward and rear facing cases, the values were below the suggested threshold limits thus confirming that it would not pose bending moment injuries to restraint older children rear facing.

Lower Neck Loads **(F_x and F_z)** - Data for lower neck loads in the x-direction, F_x are presented in Figure B-6 of Appendix "B". In all cases, the values were lower for rear facing conditions than for corresponding forward facing conditions. The graph for lower neck loads in the z-direction, F_z appears in Figure B-7 of Appendix "B". In this case, the trend is reversed in all but one case, Restraint "C" when tested with the 12-month dummy. This contradiction could not be explained from the testing and further investigation would be necessary to resolve it.

Lower Neck Moments **(M_y)** - Lower neck moments about the y-axis, M_y are graphically represented in Figure B-8 of Appendix "B". Although one data channel was lost, (Restraint "U" tested rear facing with the 12-month dummy) readings for all other tests indicate that M_y had considerably lower values for the rear facing tests as compared to the forward facing ones.

<u>**Neck Parameter Correlation**</u> - Correlation between upper and lower neck values were calculated for each test and are presented in Table 5a. It was expected that upper and lower neck values might have correlated with one another. This was the case for about half of the responses. The discrepancies between the expected performance of the dummies and the observed performance will require further research to explain.

Table 5a.
Correlation between upper and lower neck parameter for the same test

	12-month rear facing	12-month forward	18-month rear facing	18-month forward facing
Fx	-0.81	-0.86	-0.13	-0.47
Fz	0.93	0.55	0.98	0.47
My	-0.10	-0.16	-0.02	-0.91

<u>**Right and Left Shoulder Loads**</u> **(F_x and F_z)** - The right and left shoulder loads in x-direction, F_x were between four and ten times lower in the rear facing mode as compared to forward facing. This trend was reversed for the z-component of force but the difference was much less pronounced. The shoulder loads are plotted in Figures B-9, B-10, B-11 and B-12 of Appendix "B". Correlation between right and left shoulder loads were calculated for each test and are presented in Table 5b. The CanFIX were not included in this analysis. It was expected that left and right shoulder values would correlate with one another. This was the case in six out of the eight conditions.

Table 5b.
Correlation between the right and left shoulder for the same test

	12-month rear facing	12-month forward	18-month rear facing	18-month forward facing
Fx	0.45	0.97	0.72	0.89
Fz	0.93	0.77	0.94	0.36

Initial and Maximum Seat Back Tip Angles

The dynamic criteria for rear facing infant restraints that limits with the top-most part of the restraint was met in every rear-facing test even with dummies larger than which were intended. In the Canadian regulation the criterion limiting the angle of the seat back of the infant restraint with respect to the horizontal is 70 degrees from the vertical. It was met for every restraint. Graphs of seat back tip angles are presented in Appendix "C", figures C- 1 through C- 4.

RESTRAINT PERFORMANCE DIFFERENCES AND SIMILARITIES

In order to determine whether any significant differences in performance among the infant restraint systems exist, particularly as these differences relate to any significant effects due to infant restraint type, dummy size and infant restraint installation orientation (i.e., forward-facing or rear-facing) an analysis was undertaken.

Experimental Design

To accomplish this an experimental design appropriate for analyzing the test program data available had to be identified. In general, the test data lends itself to a broad class of factorial experiments composed of multifactors with repeated measures on the same elements used in the tests. Further adjustments in the analytical methods for these types of designs were made to accommodate missing test data (i.e., data was not available for all performance measures, factors and their levels from all tests carried out) which resulted in unequal cell frequencies in the design matrix. These adjustments were accounted for through the development of statistical models using 'unweighted-means' analysis methods.[41 42 43 44] These procedures are more appropriate than least-squares solutions for the test data collected in this research due to the completed experimental design has unequal group sizes because of conditions that are unrelated to the treatments. That is, the unequal cell frequencies are not the result of pre-planned stratification on the levels of the factors, i.e., infant restraint type, dummy size or restraint orientation, being investigated.

The experimental design to use, therefore, for analyzing the sled test data is that of a p x q x r factorial experiment in which there are repeated observations on the last two factors q and r. A schematic representation is given as follows:

	b_1			...	b_q		
	c_1	...	c_r	...	c_1	...	c_r
a_1	G_1	...	G_1	...	G_1	...	G_1
a_2	G_2	...	G_2	...	G_2	...	G_2
.	.		.		.		.
.	.		.		.		.
.	.		.		.		.
a_p	G_p	...	G_p	...	G_p	...	G_p

There are n_{ijk} subjects in each group. Each subject is 'potentially' observed under all qr combinations of factors b and c but only under a single level of factor a. This basic design was used for investigating whether any significant differences in performance measures (i.e., head acceleration, chest acceleration, upper neck $\{F_x, F_z, M_y\}$, lower neck $\{F_x, F_y, M_y\}$, left shoulder $\{F_x, F_z, F_r\}$, and right shoulder $\{F_x, F_y, F_r\}$) exist and whether the differences are due to the three main factors - infant restraint type, dummy size and infant restraint installation orientation (i.e., forward-facing or rear-facing).

Analytical Methods and Procedures

To illustrate the analytical methods and procedures a detailed description of the head acceleration performance measure is described here. Table 6 shows the basic head acceleration test results data within the format of the p x q x r experimental design used for this analysis. The cell means for the design are given in Table 7. Due to the fact that an unequal number of observations are in each of the cells of the basic data matrix the harmonic mean of the cell frequencies must be computed and used to compute the SS (sum of squares) used in the Analysis of Variance for the various factors and their interaction effects. The formula for computing the harmonic mean is given in equation (2.).

$$\bar{n}_h = \frac{pqr}{\sum_i \sum_j \sum_k \left(\frac{1}{n_{ijk}}\right)} \qquad (2.)$$

For our head acceleration example here $\bar{n}_h = 1.230769$.

Next the within-cell information required in the analysis is given in Table 8. Using the above information the various definitions and numerical values of the computational symbols and relevant sums of squares needed for carrying out the analysis of variance are computed and they are given as follows:

n = 2 , p = 2 , q = 2, r = 4 , $\Sigma\Sigma\Sigma n_{ijk}$ = 22 ,
G = 1032.1 , G' = 747.55 ,
(1') = [G'**2]/pqr = 34926.93766 ,
(2) = Σ(Xi**2) = 49018.85 ,
(3') = [Σ(Ai'**2)] /qr = 34963.08781 ,
(3) = [Σ(Ai**2)]/nqr = 48483.48455 ,
(4') = [Σ(Bj'**2)]/pr = 34944.68281 ,
(6') = [Σ(AB'ij**2)]/r = 34984.78313 ,
(6) = [Σ{(ABij**2)/ni}]/r = 48510.42933 ,
(7') = [Σ(AC'ik**2)]/q = 35200.50625 ,
(7) = [Σ{(ACik**2)/ni}]/q= 48718.5025 ,
(8') = [Σ(BC'jk**2)]/p = 35382.94125 ,
(9') = [Σ(ABC'ijk**2)] = 35444.9025 ,
(9) = [Σ{(ABCijk**2)/ni..}] = 48985.705 ,
(10) = [Σ{(Pm**2)/ni..}] = 48484.02458 (where ni.. is the total observations for Pm) ,
(11) = [Σ{(BPjm**2)/ni..}] = 48518.0125 (where ni.. is the total observations for BPjm) ,
(12) = [Σ{(CPkm**2)/ni..}] = 48782.57 (where ni.. is the total number of observations for CPkm).

The analysis of variance (ANOVA) for the unweighted means solution is given in Table 9. It must be noted that since all factors A, B and C are fixed the MS[w.cell] (shown in the Table) is the proper denominator to use for all significance tests.

Results

All statistical significance tests and decisions are based on a 95% level of statistical confidence. Only the head acceleration analyses are described in detail. The same type of analytical methods were designed and implemented for the other factors however, for the sake of brevity, and in the interest of focusing on the main findings only the results are discussed.

Head Acceleration - Examining Table 9 it is readily observed that the effects due to the size of the dummy have a significant impact on the head acceleration test results. Head acceleration responses are significantly higher for the 12-month old test dummy in comparison to the 18-month old dummy (i.e., the computed F[3,6] = 8.05 is larger than the tabulated $F_{.95}[3,6] = 4.76$). Also, the infant restraint orientation in the sled test (i.e., forward-facing versus rear-facing) has a significant effect on the head acceleration responses obtained with the larger head accelerations being experienced when the infant restraint is in a forward-facing position. The three-way interaction effects among the three factors being investigated was not significant implying that the variation in the head acceleration responses are not due to varying effects of the different levels of two of the factors on the third factor. Also, the two-way interaction effects of dummy size with restraint orientation and dummy size with infant restraint type are not significant. Therefore, the head accelerations are not dependent upon the joint effects of the dummy size and seat orientation or the dummy size and the restraint type. The most noteworthy finding was the significant interaction detected between the infant restraint orientation and the type of infant restraint. The head acceleration responses were significantly different - that is, the different infant

Table 6.
Basic Test Data Results for Dummy head accelerations (measured in g's)

		b 1				b 2				
	Sub-jects									Total
		c1	c2	c3	c4	c1	c2	c3	c4	388.3
a1	1	52.5	51.6	46.4	51.7	47.4	56.2	36.6	45.9	146.5
	2	52.7	45.2			48.6				
a2	3	43.7	45.7	46.9	45.8	45.0	54.7	33.1	45.9	360.8
	4	45.7				48.1			42.7	136.5

where,

a1 = 12 month old dummy size
a2 = 18 month old dummy size
b1 = front facing infant restraint system orientation
b2 = rear facing infant restraint system orientation

c1 = Restraint "T"
c2 = Restraint "S"
c3 = Restraint "C"
c4 = Restraint "U"

Table 7.
Summary table of cell means (a', b', c') for the p x q x r factorial design

	b' 1				b' 2				
	c'1	c'2	c'3	c'4	c'1	c'2	c'3	c'4	Total
a'1	52.6	48.4	46.4	51.7	48	56.2	36.6	45.9	385.8
a'2	44.7	45.7	46.9	45.8	46.55	54.7	33.1	44.3	361.75
Total	97.3	94.1	93.3	97.5	94.55	110.9	69.7	90.2	747.55 = G'
Σ Bj'	382.2				365.35				
Σ Ck'	191.85	205	163	187.7					
AB'ij	199.1				186.7				
	183.1				178.65				
AC'ik	100.6	104.6	83	97.6					
	91.25	100.4	80	90.1					

Table 8.
Summary of the within-cell information required in the analysis

		b 1				b 2			
		c1	c2	c3	c4	c1	c2	c3	c4
a1	n_{ijk}	2	2	1	1	2	1	1	1
	$\Sigma(X_{ijk})$	105.2	96.8	46.4	51.7	96	56.2	36.6	45.9
	$\Sigma(X*X)$	5533.54	4705.6	2152.96	2672.89	4608.72	3158.44	1339.56	2106.81
	SS_{ijk}	0.02	20.48	0	0	0.72	0	0	0
a2	n_{ijk}	2	1	1	1	2	1	1	2
	$\Sigma(X_{ijk})$	89.4	45.7	46.9	45.8	93.1	54.7	33.1	88.6
	$\Sigma(X*X)$	3998.18	2088.49	2199.61	2097.64	4338.61	2992.09	1095.61	3930.1
	SS_{ijk}	2	0	0	0	4.805	0	0	5.12

The pooled within-cell variation is given by: SS[w.cell] = $\Sigma\Sigma\Sigma[SS_{ijk}]$ = 33.145
The degrees of freedom for the within-cell variation, df{w.cell} = $\Sigma\Sigma\Sigma[n_{ijk}] - pqr$ = 6

Table 9.
Summary of the ANOVA

Source of Variation	Computational Formula	SS	df	MS	F
Between Subjects	(10) - (1')	13557.0869	3		
A	$\bar{n}$ [h]{(3') - (1')}	44.4925	1	44.4925	8.05
Subject w. groups[error (a)]	(10) - (3)	0.5400	2	0.2700	
Within Subjects	(2) - (10)	534.8254	28		
B	$\bar{n}$ [h]{(4') - (1')}	35.4903	1	35.4903	6.42
AB	$\bar{n}$ [h]{(6') - (3') - (4') + (1')}	4.8617	1	4.8617	0.88
B x Subject w. groups[error (b)]	(11) - (6) - (10) + (3)	7.0431	2	3.5215	
C	$\bar{n}$ [h]{(5') - (1')}	284.2959	3	94.7653	17.15
AC	$\bar{n}$ [h]{(7') - (3') - (5') + (1')}	7.9113	3	2.6371	0.47
C x Subject w. groups	(12) - (7) - (10) + (3)	63.5274	6	10.5879	
BC	$\bar{n}$ [h]{(8') - (4') - (5') + (1')}	255.0990	3	85.0330	15.39
ABC	$\bar{n}$ [h]{(9') - (6') - (7') - (8') + (3') + (4') + (5') - (1')}	18.9944	3	6.3314	1.14
BC x Subject w. groups[error (bc)]	(2) - (9) - (11) - (12) + (6) + (7) + (10) - (3)	-37.9656	6	-6.3276	
Within cell	(2) - (9)	33.145	6	5.5241	

restraint systems generate significantly different head accelerations depending upon the orientation of the restraint system (i.e.; forward-facing or rearward-facing).

Chest Acceleration - Unlike the head acceleration results the dummy size did not produce significantly different chest accelerations. On the other hand, the chest accelerations are significantly higher for infant restraint systems oriented in the forward-facing than in the rear-facing position. Significant differences in chest acceleration results were also found for the different infant restraint systems. All two-way interaction effects were also found to be statistically significant (i.e., dummy size and restraint orientation, dummy size and infant restraint type, and restraint orientation and infant restraint type). This means that the chest acceleration responses are significantly different for all three factors, with the differences being dependent upon the level of another factor present in the sled test. Finally, unlike the head acceleration results, the chest acceleration responses are not significantly affected by the joint three-way interaction of all three factors. In other words the chest acceleration responses are not significantly affected or dependent upon the level of any of the three factors present in a particular sled test.

Upper Neck Loads (F_x) - The results of these analyses revealed that only the infant restraint orientation (i.e., forward-facing versus rear-facing) has a significant effect on the upper neck load x-component. The rear-facing loads are statistically significantly lower than the forward-facing. Neither of the other two factors (i.e., dummy size or infant restraint type) had a significant effect on the variations in the F_x responses. Also, none of the two-way interactions among the three factors nor the three-way interaction has a significant impact upon the F_x responses in the sled tests.

Upper Neck Loads (F_z) - The upper neck loads in the z-direction are significantly affected by the infant restraint orientation and the type of infant restraint. The size of the dummy has no significant impact upon the F_z results obtained. The only significant interaction effect identified was the infant restraint orientation by infant restraint type – the F_z responses are significantly dependent upon the restraint type and its orientation.

Upper Neck Moments (M_y) - The results of the analyses performed on the upper neck moments (M_y) responses from the sled tests revealed that none of the factors, non of the two-way interactions of the factors, nor the three-way interaction of the three factors has a significant effect on the M_y responses observed. In other words, the M_y responses are not significantly different for different dummy size, infant restraint orientation, infant restraint type, interactions of any of the levels of the two factors, or the three-way interaction of the factors.

Lower Neck Loads (F_x) - The ANOVA findings revealed that only the infant restraint orientation was a significant factor affecting the lower neck F_x's in the sled tests. The dummy size and infant restraint type did not have an appreciable affect on the F_x responses. Also, non of the two-way or the three-way interactions among the three factors provided any significant ability to predict the lower neck F_x loads.

Lower Neck Loads (F_z) - Contrary to the results found for the lower neck F_x loads, the analyses of the z-direction lower neck loads (F_z) identified a number of significant factors affecting the responses. All of the factors (dummy size, infant restraint orientation and infant restraint type) are significant with respect to the lower neck F_z sled test responses. This means that the lower neck F_z results are dependent upon all three factors – the significant differences depend upon the dummy size, infant restraint orientation and infant restraint type. Among the three two-way and the three-way interaction effects only one interaction effect is found to be statistically significant – the interaction of the dummy size and the infant restraint orientation. This implies that the lower neck F_z loads are statistically different for different dummy size and infant restraint orientation. In other words, the response loads are dependent upon the size of the dummy and the orientation of the infant restraint.

Lower Neck Moments (M_y) – From the analysis of variance carried out on the lower neck moments only one of the factors has a significant effect on the responses observed from the sled tests – the infant restraint orientation. Neither of the other two factors (i.e., dummy size or infant restraint type) nor any of the three two-way or the three-way interactions is a significant factor in explaining the source of variation among the lower neck moments (M_y) responses. Therefore, only the orientation of the infant restraint system – forward-facing versus rear-facing – has a significant effect on the level of lower neck M_y response. The responses are significantly smaller for the rear-facing orientation.

Left Shoulder Loads (F_x) – As in the case of the lower neck moments (M_y) above, the only factor that has a significant impact on the level of left shoulder loads observed among the sled tests is the infant restraint orientation. The left shoulder F_x's are significantly smaller for the rear-facing orientation than the forward-facing position. Neither the dummy size or the infant restraint type have an appreciable effect on the left shoulder F_x loads, nor do any of the two-way or the three-way interactions among the factors.

Left Shoulder Loads (F_z) – The findings of the analyses conducted on the left shoulder loads in the z-direction revealed the same results as the lower neck moments and the left shoulder F_x loads. The only significant factor having the capacity to explain variations in the left should F_z loads of the sled tests being the infant restraint orientation. The major difference, however, is that the rear-facing restraint orientation generates significantly higher F_z responses than the forward-facing restraint position.

Right Shoulder Loads (F_x) – These results differed considerably from those found for the left shoulder F_x response loads. Only dummy size has a significant effect on the responses observed in the case of the left shoulder F_x loads, whereas all three factors (i.e., dummy size, infant restraint orientation and infant restraint type) have significant impacts on the levels of response for the right shoulder F_x loads observed in the sled tests. Further differences resulted with respect to interactions – none were found in the case of the left shoulder forces in the x-direction, but the interactions of dummy size and infant restraint type, infant restraint orientation and infant restraint type, and the three-way interaction of dummy size by infant restraint orientation by infant restraint type are all significant components for explaining the variation among the right shoulder F_x responses in the sled tests. One of the most significant observations to note is how small the right shoulder F_x forces are in the rear-facing infant restraint orientation compared to the forward-facing position.

Right Shoulder Loads (F_z) – Quite different results were found for the right shoulder loads in the z-direction than for the F_z left shoulder responses. All three factors are statistically significant with respect to explaining variations among the right shoulder F_z responses, but only the infant restraint orientation has a significant effect on the level of left shoulder F_z response observed in the sled tests. Also the interaction effect due to the dummy size and infant restraint orientation as well as that due to infant restraint orientation and infant restraint type have significant impacts on the right shoulder loads in the z-direction. In contrast, no interaction effects whatsoever among the three factors were detected among the left shoulder F_z responses.

RELIABILITY OF MEASUREMENTS

In any experimental design involving test procedures and measuring devices there is always potential for sources of error to occur thereby affecting the resultant measurements. It is important that the amount of measurement error is known so that the results can be properly interpreted and also for making improvements in subsequent studies. Stewart[45] developed and implemented methodology for assessing the reliability of emission gas response estimates measured in Transport Canada's Emission Test Program on Methanol Fuels. The following sections present modified methodology based on this work for quantifying the amounts of measurement error present in the sled tests involved in the present research study and the implementation of these methods to measure the reliability of the responses obtained for each of the response variables measured.

Methodology

Given that a particular unit of a population possesses a magnitude π of a specified characteristic. In the measurement of this characteristic with some measuring device the observed score may have the magnitude $\pi + \eta$, where η is the 'error of measurement' – all measurements have some amount of this type of error. The amount of error due to η is in part due to the measuring device itself and in part due to the conditions surrounding the actual measurement. Therefore, a measurement on unit i with measuring instrument j may be represented as

$$X_{ij} = \pi_i + \eta_{ij} \qquad (3.)$$

where,

X_{ij} **= observed measurement,**

π_i **= true magnitude of characteristic being measured,**

η_{ij} **= error of measurement.**

Upon repeated measurement with the same or comparable instruments, π_i is assumed to remain constant, whereas η_{ij} is assumed to vary. The mean of k such repeated measures may be represented as shown in equation (4.).

$$\left(\sum_j X_{ij}\right)\Big/ k=\overline{P_i}=\pi_i+\overline{\eta_i}\,. \qquad (4.)$$

A schematic representation of the data for a random sample of k measurements on the same or comparable measuring instruments is provided in Table 10.

Given that π_i remains constant for all measurements, the variance within unit i is due to error of measurement, and the pooled within-unit variance also estimates variance due to error of measurement. On the other hand, the variance in the $\overline{P_i}$'s is due in part to differences between the true magnitudes of the characteristic possessed by the η units and in part due to differences in the average error of measurement for each unit. The analysis of variance (ANOVA) and the expected values for the mean squares for data of this type are given in Table 10.

Table 10.
Estimation of Reliability

	Comparable Measurements								
Unit	1	2	2	...	j	...	k	Total	Mean
1	X_{11}	X_{12}	X_{13}	.	X_{1j}	.	X_{1k}	P_1	$\overline{P_1}$
2	X_{21}	X_{22}	X_{23}	.	X_{2j}	.	X_{2k}	P_2	$\overline{P_2}$
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
i	X_{i1}	X_{i2}	X_{i3}	.	X_{ij}	.	X_{ik}	P_i	$\overline{P_i}$
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
n	X_{n1}	X_{n2}	X_{n3}	.	X_{nj}	.	X_{nk}	P_n	$\overline{P_n}$
Total	$\overline{T_1}$	$\overline{T_2}$	$\overline{T_3}$	...	$\overline{T_j}$	...	$\overline{T_k}$	$\overline{G}$	

$MS_{b.units}$ is defined in equation (5.).

$$MS_{b.units}=k\sum\left(\overline{P_i}-\overline{G}\right)^2\Big/(n-1) \qquad (5.)$$

Table 11.
Analysis of Variance for Model in (3.)

Source of Variation	MS	E(MS)
Between units	$MS_{b.units}$	$\sigma^2_\eta + k\,\sigma^2_\pi$
Within units	$MS_{w.units}$	σ^2_η

and the variance of the P's given in equation (6.).

$$s^2_{\overline{P}}=\sum\left(\overline{P_i}-\overline{G}\right)^2\Big/(n-1) \qquad (6.)$$

Therefore, $\qquad MS_{b.units}=k\; s^2_{\overline{P}}$

In terms of (4.), the expected value of the variance of the P's is given by,

$$E\left(s^2_{\overline{P}}\right)=\sigma^2_{\overline{\eta}}+\sigma^2_{\pi}.$$

The quantity σ^2_{π}. is the variance of the true measures in the population of which the n units in the study represent a random sample. From the relationship between $MS_{b.units}$ and $s^2_{\overline{P}}$ we have,

$$E\left(MS_{b.units}\right)=k\,\sigma^2_{\overline{\eta}}+k\,\sigma^2_{\pi}$$

since $\qquad k\,\sigma^2_{\overline{\eta}}=\sigma^2_{\eta}.$

The reliability of $\overline{P_i}$, the mean of k measurements, is defined as

$$\rho_k=\frac{\sigma^2_\pi}{\sigma^2_\pi+\sigma^2_{\overline{\eta}}}=\frac{\sigma^2_\pi}{\sigma^2_\pi+\left(\sigma^2_\eta/k\right)} \qquad (7.)$$

This is interpreted as the reliability of the mean of k measurements is the variance due to true scores divided by the sum of the variance due to true scores and the variance due to the mean of the errors of measurement. If we define,

$$\theta=\sigma^2_\pi\Big/\sigma^2_\eta\,,$$

then the formulae for ρ_k may be written in the form

$$\rho_k=\frac{k\theta}{1+k\theta} \qquad (8.)$$

Therefore, when k = 1, (8.) becomes,

$$\rho_1=\frac{\theta}{1+\theta}=\frac{\sigma^2_\pi}{\sigma^2_\pi+\sigma^2_\eta} \qquad (9.)$$

which, by definition, is the reliability of a single measurement. Within the context of the variancecomponent model of the analysis of variance, (8.) represents the *intraclass* correlation.

Results

The above methodology was implemented to assess the reliability of the measurements taken on head accelerations, chest accelerations, upper neck loads (F_x, F_z) and moments (M_y), lower neck loads (F_x, F_z) and moments (M_y), left shoulder loads (F_x, F_z) and right shoulder loads (F_x, F_z). It must be noted that some cells of the three factor experimental design (dummy size, infant restraint orientation and infant restraint type) for which measurements on each of the above response variables were sought are not available. That is because some of the data on certain response variables was lost during the sled test. In some instances there were no responses obtained for a particular factor in a sled test. As a result, the reliability of measurement analyses presented here only includes the experimental design cells for each of the response variables above where there are two measurements (i.e., two sled test measurements were obtained). This is because reliability indicators can only be measured for response variables that have two or more comparable measurements. The results for all reliability tests carried out are provided in Table 12. The following summarizes the findings.

<u>Head Acceleration</u> – Two measurements available on the head acceleration response variable results in a reliability estimate of 0.700 (or 70 %). This is interpreted as two comparable measurements on head acceleration (i.e., two tests done for the same dummy size, infant restraint orientation and infant restraint type) results in an average measurement that is 70 % reliable, or in other words, an error of +/- 15 % of the average of two measurements on the head acceleration response variable will contain the true population head acceleration response value. As can also be seen from the table, if only one measurement is taken then the reliability of the head acceleration response drops considerably down to 53.8 %.

<u>Chest Accelerations</u> – The reliability of the chest acceleration responses is significantly higher than that of the head accelerations. Two measurements for the same dummy size, infant restraint orientation and infant restraint type results in an average chest acceleration response measurement that is 96.3 % reliable – an error of less than +/- 2 %. Even one sled test for each of the dummy sizes, infant restraint orientations and infant restraint types would produce responses that are 92.9 % reliable.

<u>Upper Neck Loads</u> (F_x) - The results for the upper neck loads in the x-direction are nearly identical to the chest acceleration findings. Two measurements per cell of the experimental design generates an average upper neck F_x response estimate that is 96.7 % reliable. If only one measurement were available per cell the reliability would still be 93.5 %.

<u>Upper Neck Loads</u> (F_z) – The upper neck loads in the z-direction are not nearly as reliable as those in the x-direction. The reliability of the mean of two measurements on F_z for a given dummy size, infant restraint orientation and infant restraint type in a sled test is 86.1 %. Therefore, the errors surrounding the mean of these two sled tests is +/- 7 %. One sled test measurement would only result in an upper neck F_z response measurement that is only 75.6 % reliable.

<u>Upper Neck Moments</u> (M_y) – The upper neck moments (M_y) are not reliable at all. Two comparable measurements on the same dummy size, infant restraint orientation and infant restraint type yields a mean estimate that is only 18.5% reliable. This means that the true population value of the upper neck moment (M_y) is somewhere within the range of the mean +/- 42 %. A single sled test would produce upper neck M_y's that are only 10.2 % reliable. Clearly, there is a need to improve the measurement devices and procedures for minimizing the error surrounding the upper neck moments (M_y) response variables. Otherwise, a very large number of sled tests is required to generate results that even begin to reflect the true population value of the upper neck M_y's.

<u>Lower Neck Loads</u> (F_x) – The reliability of these response variables are also quite low. Two measurements on the same dummy size, infant restraint orientation and infant restraint type only generates a mean value that has a 63.5 % reliability – the mean has error bounds of +/- 18 %. If only one measurement were taken per cell of the experimental design than the reliability of the lower neck F_x loads drops further to 46.5 %.

<u>Lower Neck Loads</u> (F_z) – The lower neck loads in the z-direction show responses that appear to be quite reliable. A 95.7 % level of reliability is attained with two measurements on the same dummy size, infant restraint orientation and infant restraint type. If only one measurement is taken the reliability is still in the order of 92 %.

<u>Lower Neck Moments</u> (M_y) – Very reliable results are indicated in the case of the lower neck moments

(M_y). An unprecedented 96.4 % reliability is attained with two measurements on the same dummy size, infant restraint orientation and infant restraint type. Even if only a single measurement is obtained per cell of the experimental design the lower neck moments (M_y) still enjoy a 93.1 % level of reliability.

Left Shoulder Loads **(F_x)** – The left shoulder loads in the x-direction are extremely reliable. Two measurements within the same cell of the experimental design matrix produce a mean estimator that has a 97.9 % reliability associated with it. This means that the true population value of the left shoulder F_x loads is contained within the mean +/- 1 %. A single measurement (i.e., only one sled test) for a given dummy size, infant restraint orientation and infant restraint type yields a response value that is 95.9 % reliable.

Left Shoulder Loads **(F_z)** – The left shoulder loads in the z-direction are no where near as reliable as those in the x-direction. Two sled tests on the same dummy size, infant restraint orientation and infant restraint type results in a mean estimator of left shoulder F_z that is 86.5 % reliable – the true population value is somewhere within the mean +/- 7 %. If only a single sled test is conducted for a particular dummy size, infant restraint orientation and infant restraint type then the level of reliability falls appreciably some to 76.3 %.

Right Shoulder Loads **(F_x)** – The right shoulder loads in the x-direction have the highest reliability of any of the response variables. Two measurements on the same dummy size, infant restraint orientation and infant restraint type result in a mean estimator that is 99.4 % reliable. In other words, the true population value of the right shoulder F_x load is found within the mean +/- 0.3 %. Even if only one sled test is performed the singe measurement has a 98.8 % level of reliability associated with it.

Right Shoulder Loads **(F_z)** – Although not quite as high as the right shoulder loads in the x-direction, the right shoulder loads in the z-direction are still extremely reliable. Two measurements on the same dummy size, infant restraint orientation and infant restraint type yield a mean that has a reliability of 96.5 % - or the true population value is within the range of the mean +/- 1.75 %. If only one sled test is performed for a particular dummy size, infant restraint orientation and infant restraint type the level of reliability of the resulting response variable is still high, at 93.3 %.

Table 12.
Reliability of Response Variable Measurements

Response Variable	Number of Comparable Measures	Reliability (%)
Head Accelerations	1	53.8
	2	70.0
Chest Accelerations	1	92.9
	2	96.3
Upper Neck Loads (F_x)	1	93.5
	2	96.7
Upper Neck Loads (F_z)	1	75.6
	2	86.1
Upper Neck Moments(M_y)	1	10.2
	2	18.5
Lower Neck Loads (F_x)	1	46.5
	2	63.5
Lower Neck Loads (F_z)	1	91.8
	2	95.7
Lower Neck Moments(M_y)	1	93.1
	2	96.4
Left Shoulder Loads (F_x)	1	95.9
	2	97.9
Left Shoulder Loads (F_z)	1	76.3
	2	86.5
Right Shoulder Loads (F_x)	1	98.8
	2	99.4
Right Shoulder Loads (F_z)	1	93.3
	2	96.5

From the results of the "reliability of measurements" analyses conducted the '22 sled test program' generated estimates on the response variables that are:

(i) at least 95% reliable for chest accelerations, upper neck loads in the x-direction, lower neck loads in the z-direction, lower neck moments (My), left shoulder loads in the x-direction, right should loads in the x-direction, and right shoulder loads in the z-direction, given two sled tests are performed on a particular dummy size, infant restraint orientation and infant restraint type; and

(ii) at least 95% reliable for left shoulder loads in the x-direction and right shoulder loads in the x-direction given one sled test was performed on a particular dummy size, infant restraint orientation and infant restraint type;

In general two sled tests carried out for a particular dummy size, infant restraint orientation and infant restraint type generates response estimates that are 95%

reliable for all variables with the exception of head accelerations, upper neck loads in the z-direction, upper neck moments (My), lower neck loads in the x-direction, and left shoulder loads in the z-direction. To improve the estimators for these response variables it is necessary to either improve the test method and procedures (to generate more controlled and accurate responses) or increase the number of tests to a sufficient number to attain a level of 95% reliability.

If the number of tests were increased to attain a 95% level of reliability for the response variables above that fell short of this criterion, then the number of tests required for each for a particular dummy size, infant restraint orientation and infant restraint type would be as follows:

Response Variable	**# Tests Required**
Head accelerations	12
Upper neck loads (F_z)	7
Upper neck moments (M_y)	168
Lower neck loads (F_x)	22
Left shoulder loads (F_z)	6

It must be noted, however, that the number of test results acquired for each response variable in this research was not two consistently. Some response variable results are entirely missing or only have one test result due to lost data in some of the 22 sled tests conducted. It is therefore expected that some of the reliability on the measurements for the above five response variables would be significantly improved if future programs ensured that all data is captured from each sled test.

CONCLUSIONS AND DISCUSSIONS

From this study, the following conclusions have been drawn:

- Infants and young toddlers, are provided with a higher level of safety when restrained in a rear facing infant restraint system as long as possible rather than not being restrained, being restrained in a forward facing restraint or restrained by a seat belt.

- The results of the ANOVA revealed that all response variables, with the exception of the upper neck moment (M_y) and the right shoulder (F_x) loads, were significantly affected by the orientation of the restraint. Furthermore, the responses are all smaller for the rear facing orientation than the forward facing ones.

- Even though the current Canadian criteria for infant restraints are in place for the 6- and a 9-dummies, convertible restraints that were tested rear facing with larger 12-, 18- and 3-year old dummies meet them.

- Generally, the head and chest acceleration, upper and lower neck loads and moments were lower for a comparable set of test conditions for the rear facing orientation as compared to forward facing. The exception to this was the lower neck loads, F_z where the opposite was observed.

- Generally the shoulder loads were produced considerably lower values for a comparable set of test conditions for the rear facing orientation as compared to forward facing for the x-component. The reverse was true in the z-direction but the difference was much less. However in the absence of any injury threshold criteria for child shoulders, it could not be determined if these higher loads in the z-direction would be injurious. However shoulder related injuries have not been reported by countries where children up to three and four years are restrained rear facing.

- In addition to permitting the use of larger dummies than currently specified, the next step in the process to ensure that rear-facing restraints are available more widely in Canada is to determine what benefits would be gained from specifying maximum head and chest acceleration, neck load and moments and shoulder load maximums in the regulations.

- In all cases, the structural integrity of the restraint was intact indicating that little redesign would be need of restraint manufacturers to adapt their restraints for larger children in the rear facing installation.

- A series of tests of North American convertible restraints on the standard bench seat with a simulated dash similar to that of ECE Reg. 44 should be envisaged since the larger restraints meant to restrain larger children may be more realistically tested in that manner.

- Although a better performer in the majority of cases, the CanFIX, a restraint rigidly attached at its base to the standard test bench, did not consistently perform better rear facing compared to forward facing. Further investigating the effect of rigidly attached restraint base may be necessary since the testing was performed with an early prototype of the CanFIX.

- Reconstructions with the 12- and 18-month dummies are required to establish threshold limits for the neck.

- Additional research in shoulder injuries to restrained children is required to.

- Although it must be re-iterated that the results provided for the field data are subject to high levels of error (due to the small sample sizes they comprise within the entire PCS data bases) the trend is quite evident. A strong correlation between incorrect restraint installation, improper restraint use and the probability of sustaining an injury or fatality is quite apparent. It is therefore necessary to work towards improving protection for infants through mechanisms such as regulating aspects of the various restraint system products to increase both their correct installation and proper use.

- From the results of the "reliability of measurements" analyses conducted the '22 sled test program' generated estimates on the response variables that are:

  (i) at least 95% reliable for chest accelerations, upper neck loads in the x-direction, lower neck loads in the z-direction, lower neck moments (My), left shoulder loads in the x-direction, right should loads in the x-direction, and right shoulder loads in the z-direction, given 2 sled tests are performed on a particular dummy size, infant restraint orientation and infant restraint type.

  (ii) at least 95% reliable for left shoulder loads in the x-direction and right shoulder loads in the x-direction given 1 sled test was performed on a particular dummy size, infant restraint orientation and infant restraint type.

- In general two sled tests carried out for a particular dummy size, infant restraint orientation and infant restraint type generate response estimates that are 95% reliable for all variables with the exception of head accelerations, upper neck loads in the z-direction, upper neck moments (M_y), lower neck loads in the x-direction, and left shoulder loads in the z-direction. To improve the estimators for these response variables it is necessary to either improve the test method and procedures (to generate more controlled and accurate responses) or increase the number of tests to a sufficient number to attain a level of 95% reliability.

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DISCLAIMER

The responsibility for the results presented herein rests entirely with the authors. The conclusions drawn are those of the authors alone and do not necessarily reflect the views of Transport Canada.

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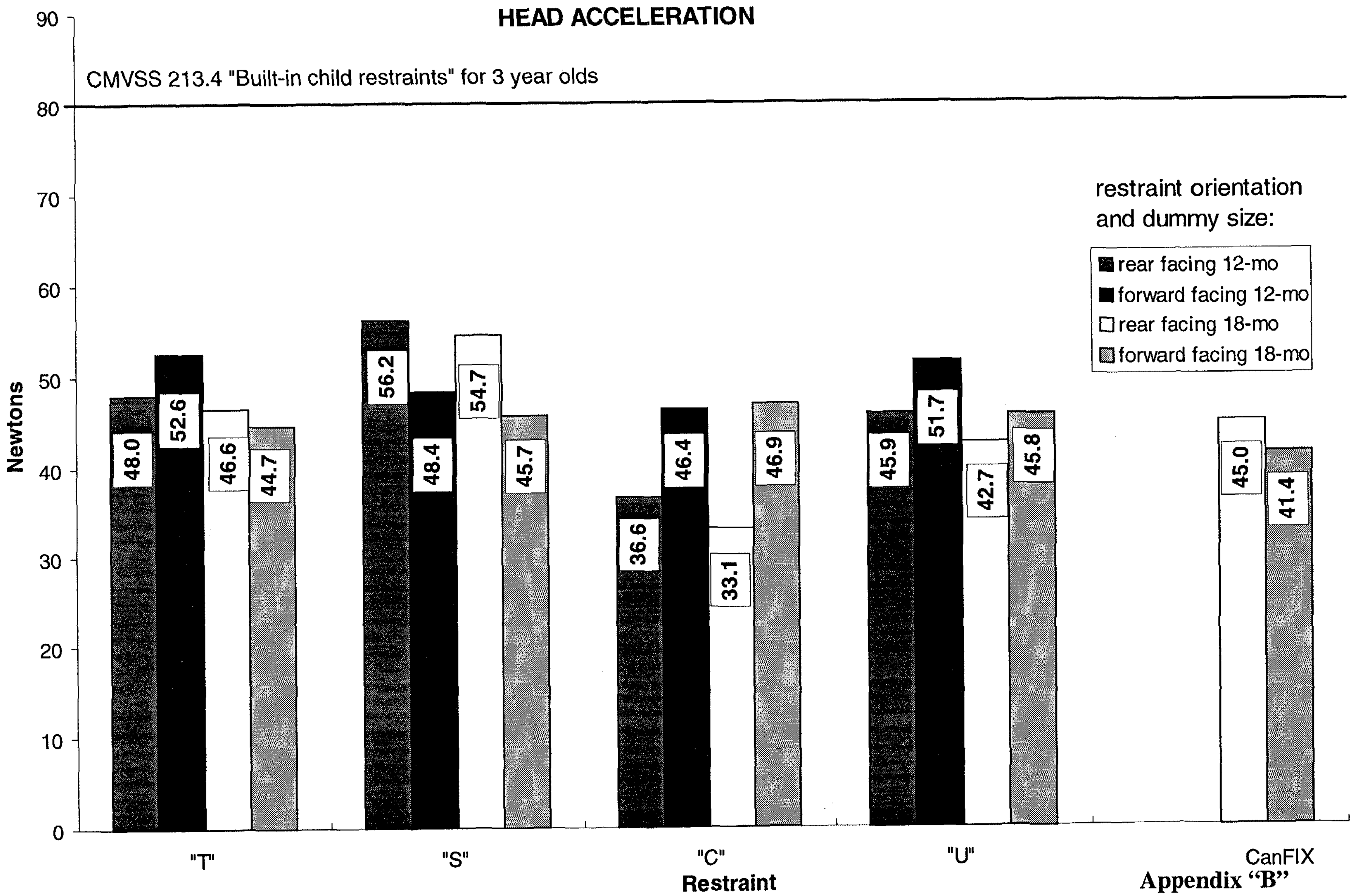

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Appendix "B"

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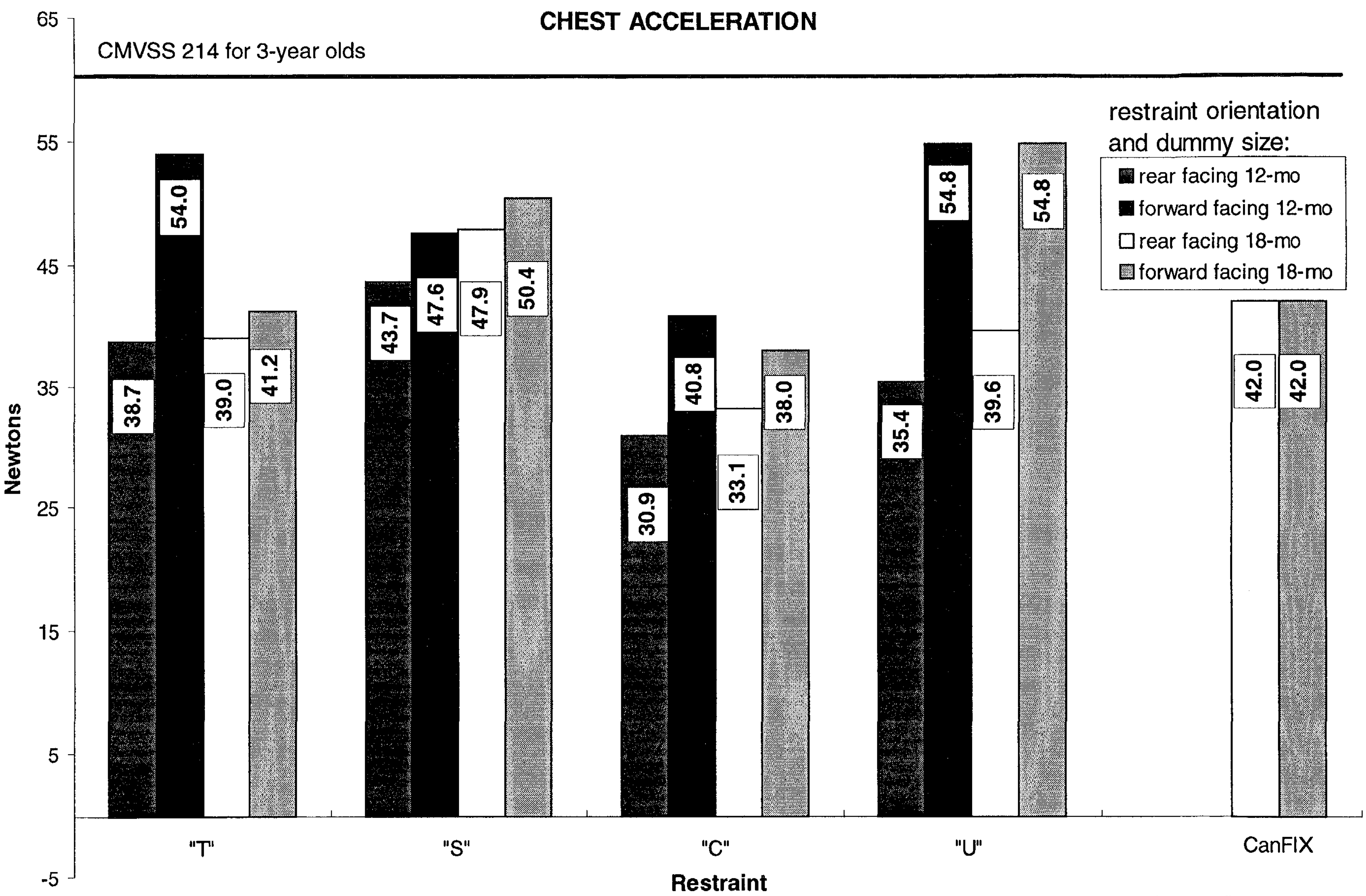

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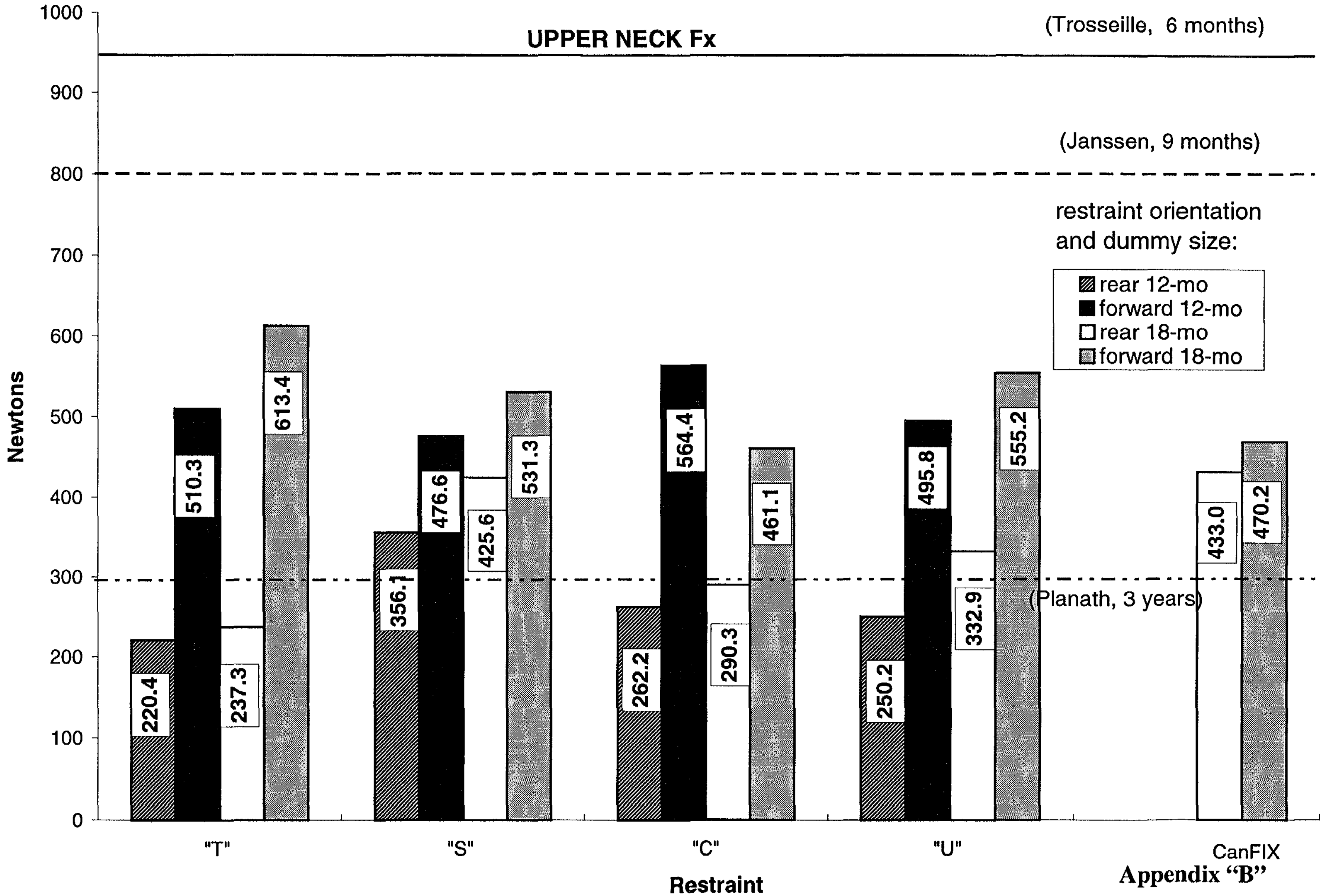
Figure "B-2"



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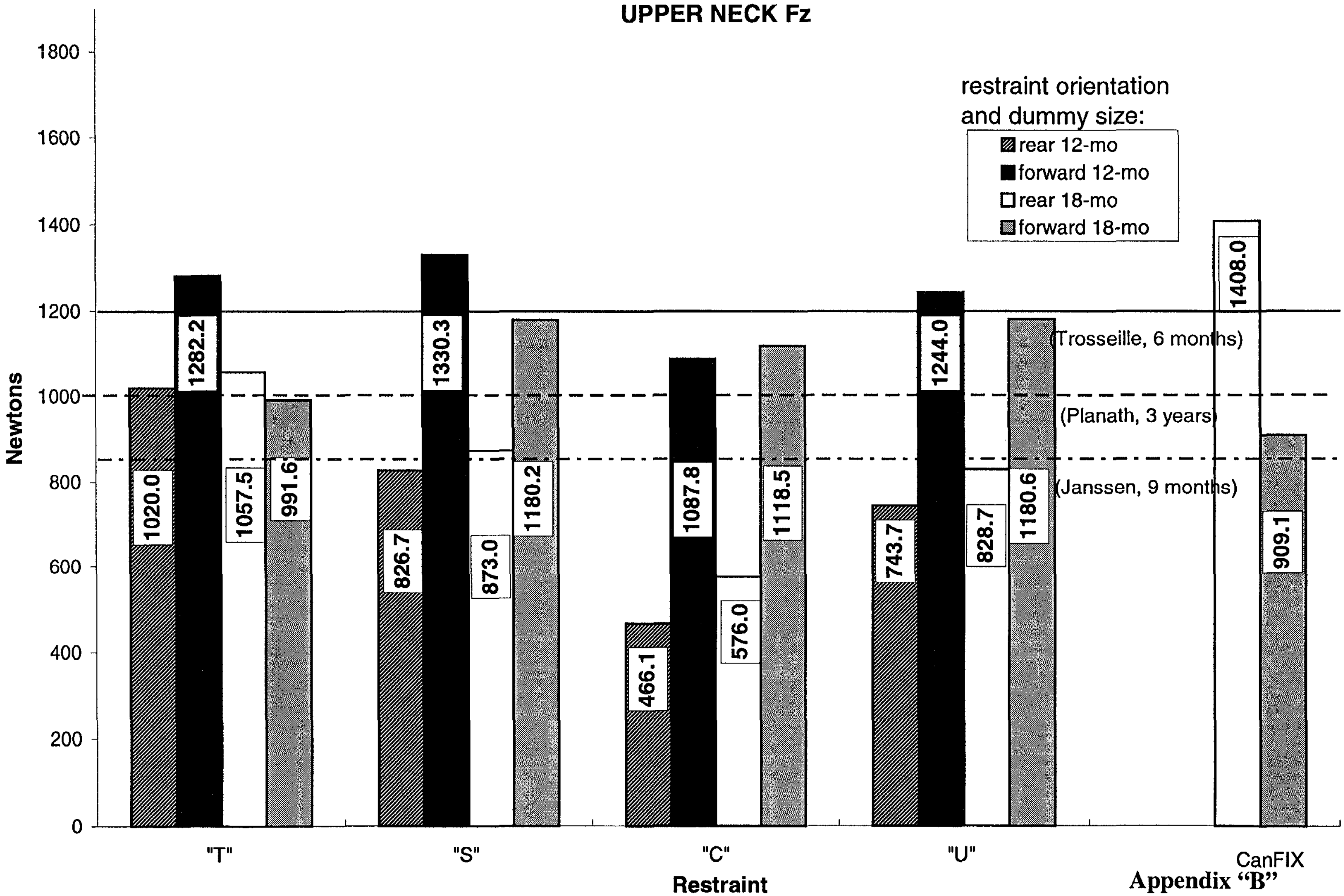

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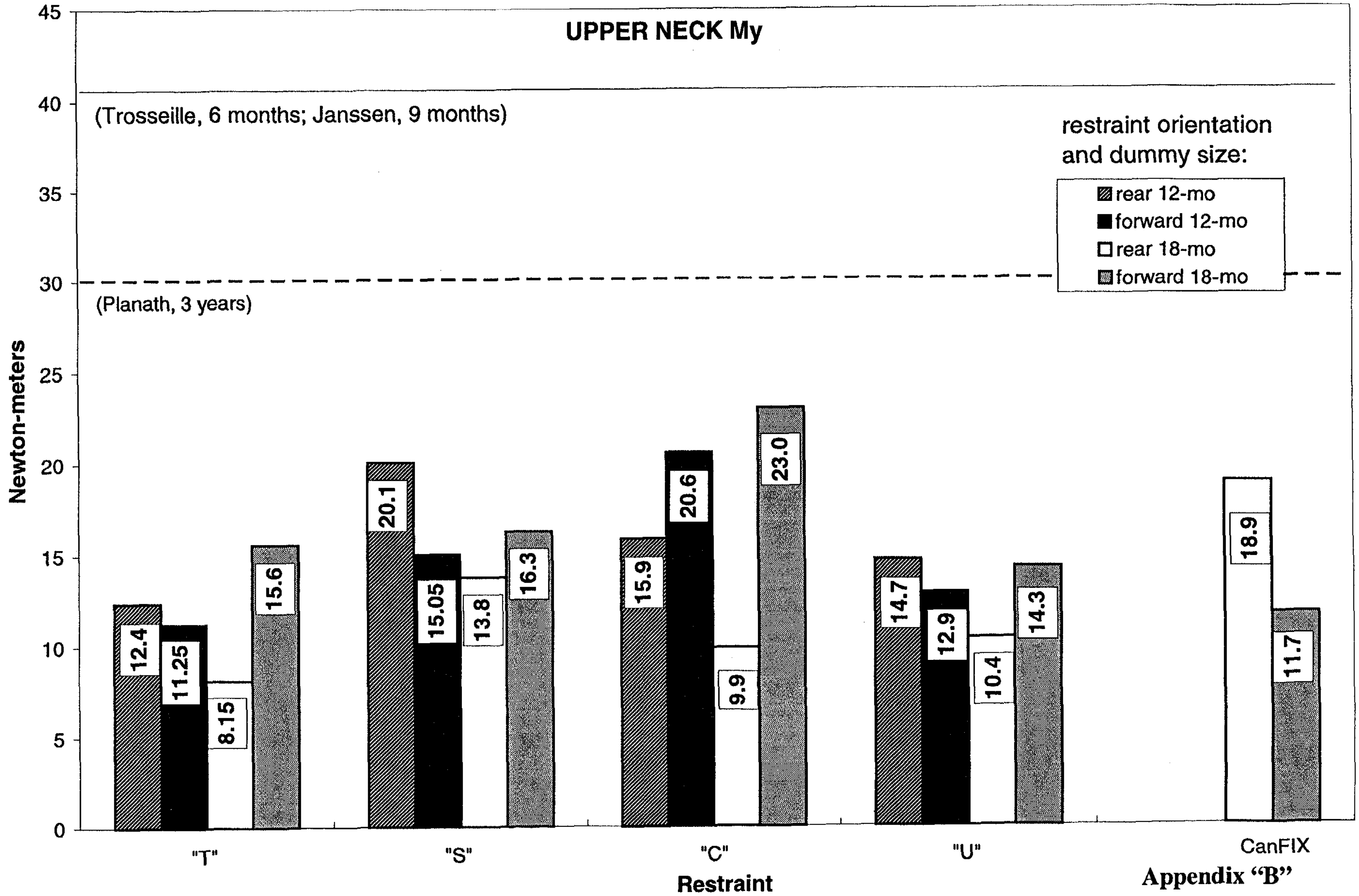

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Figure "B-5"

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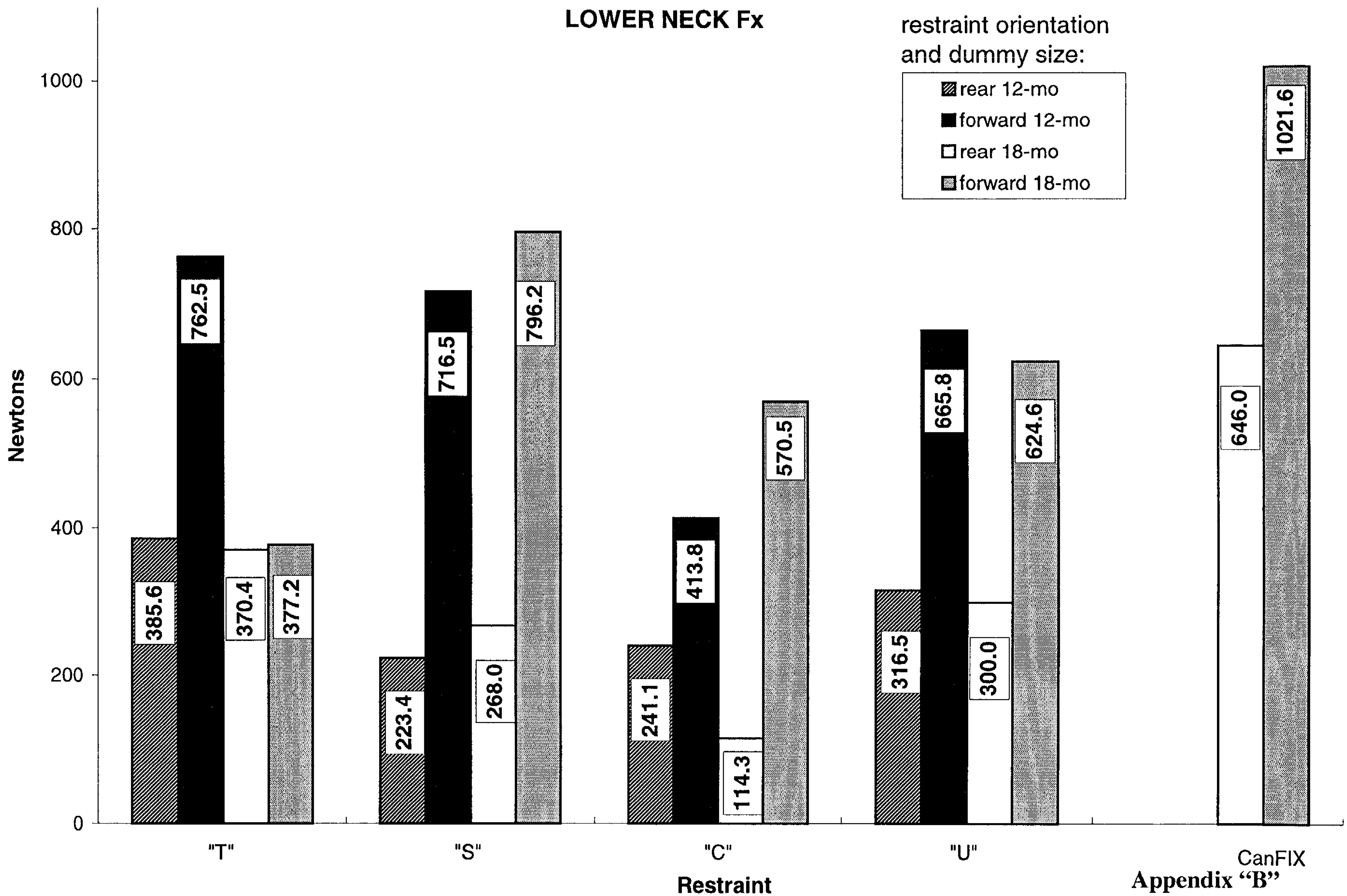

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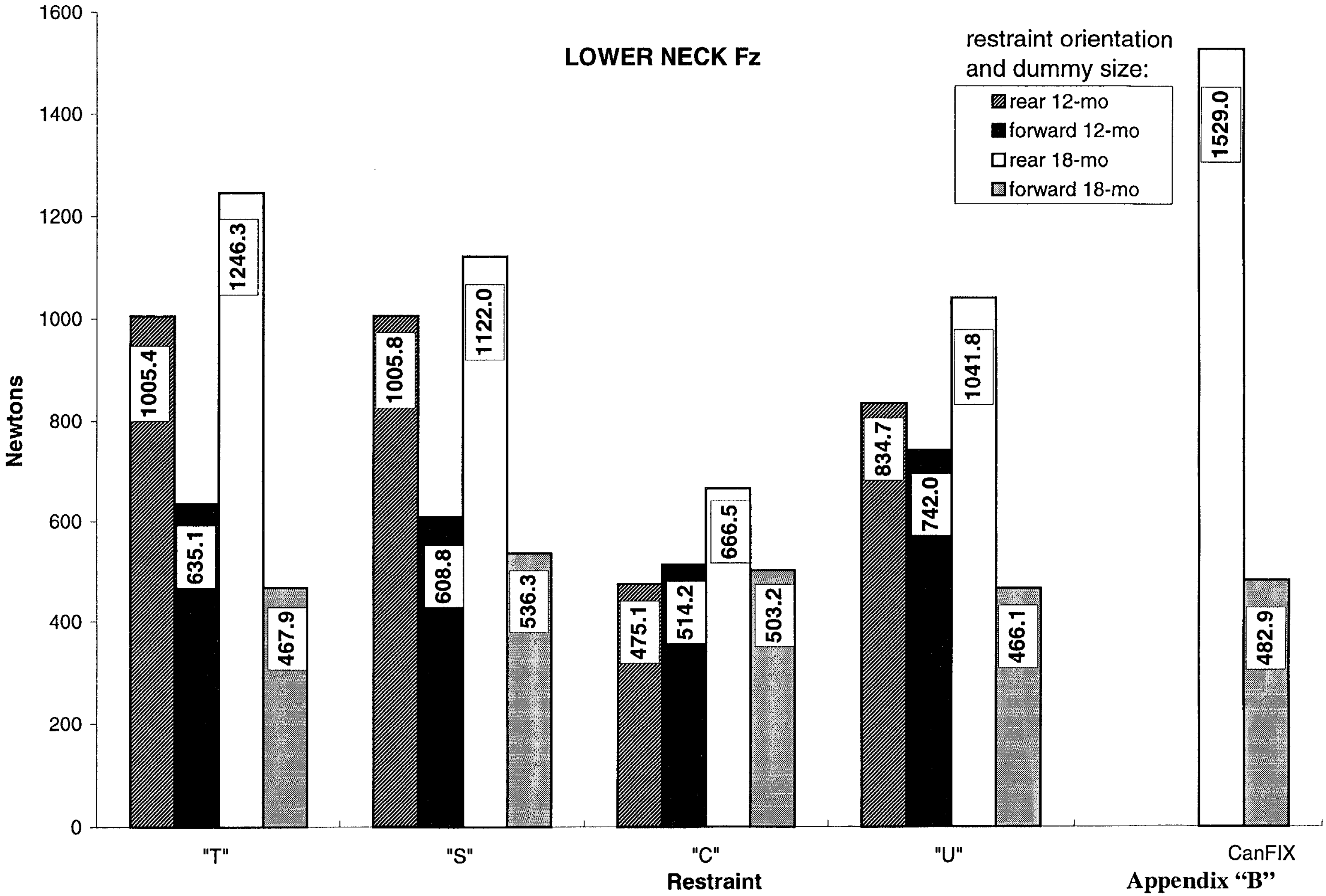

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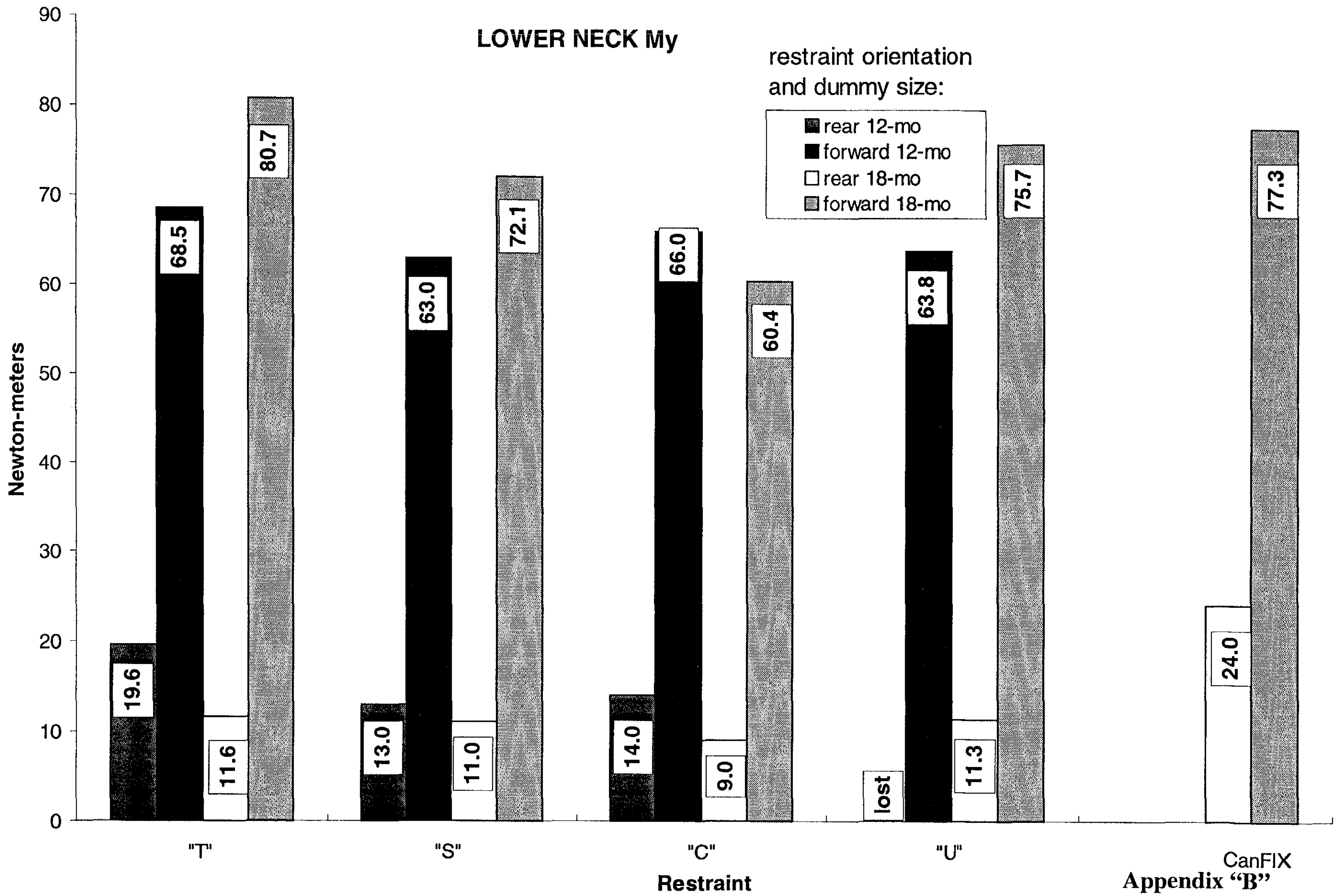

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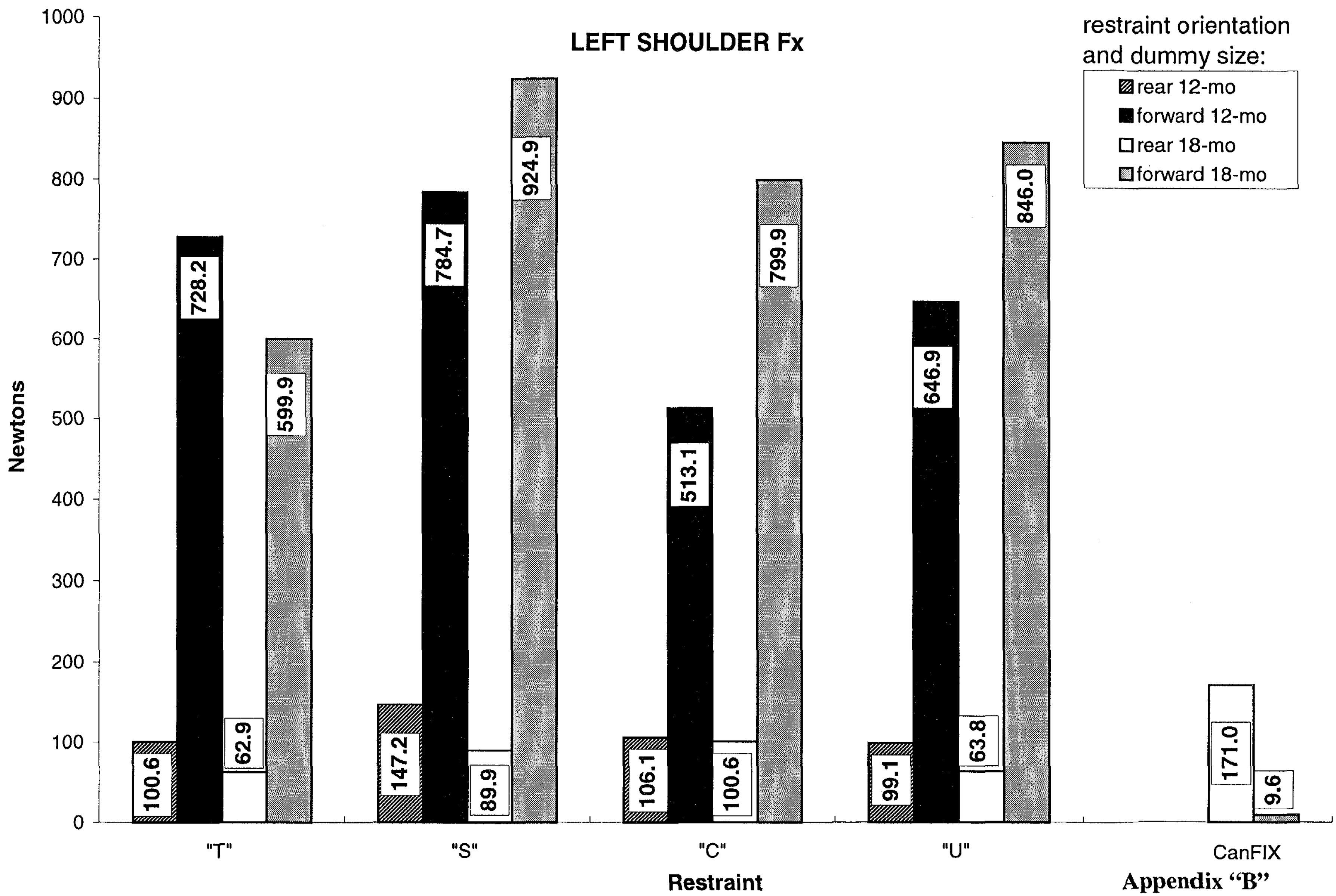

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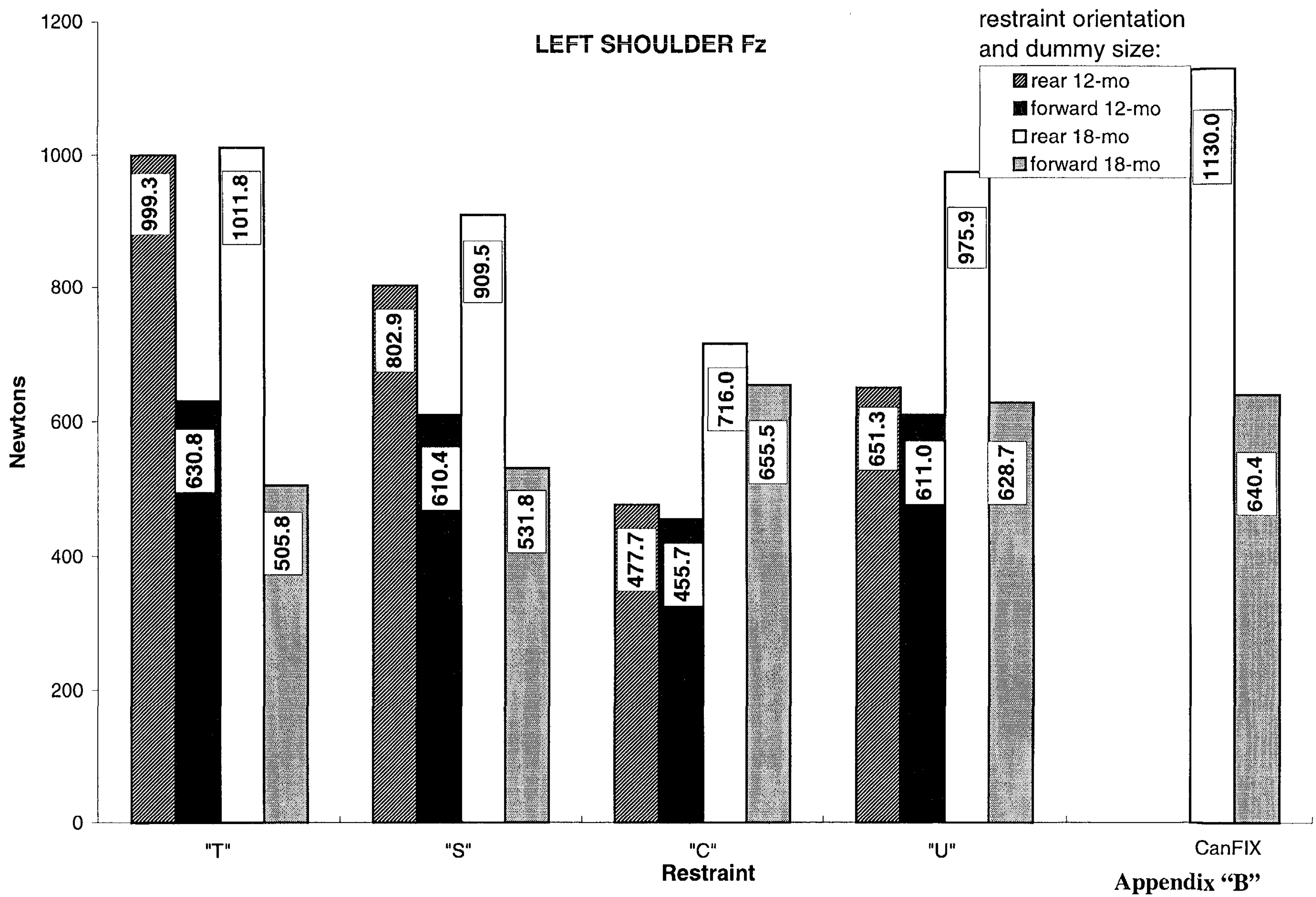

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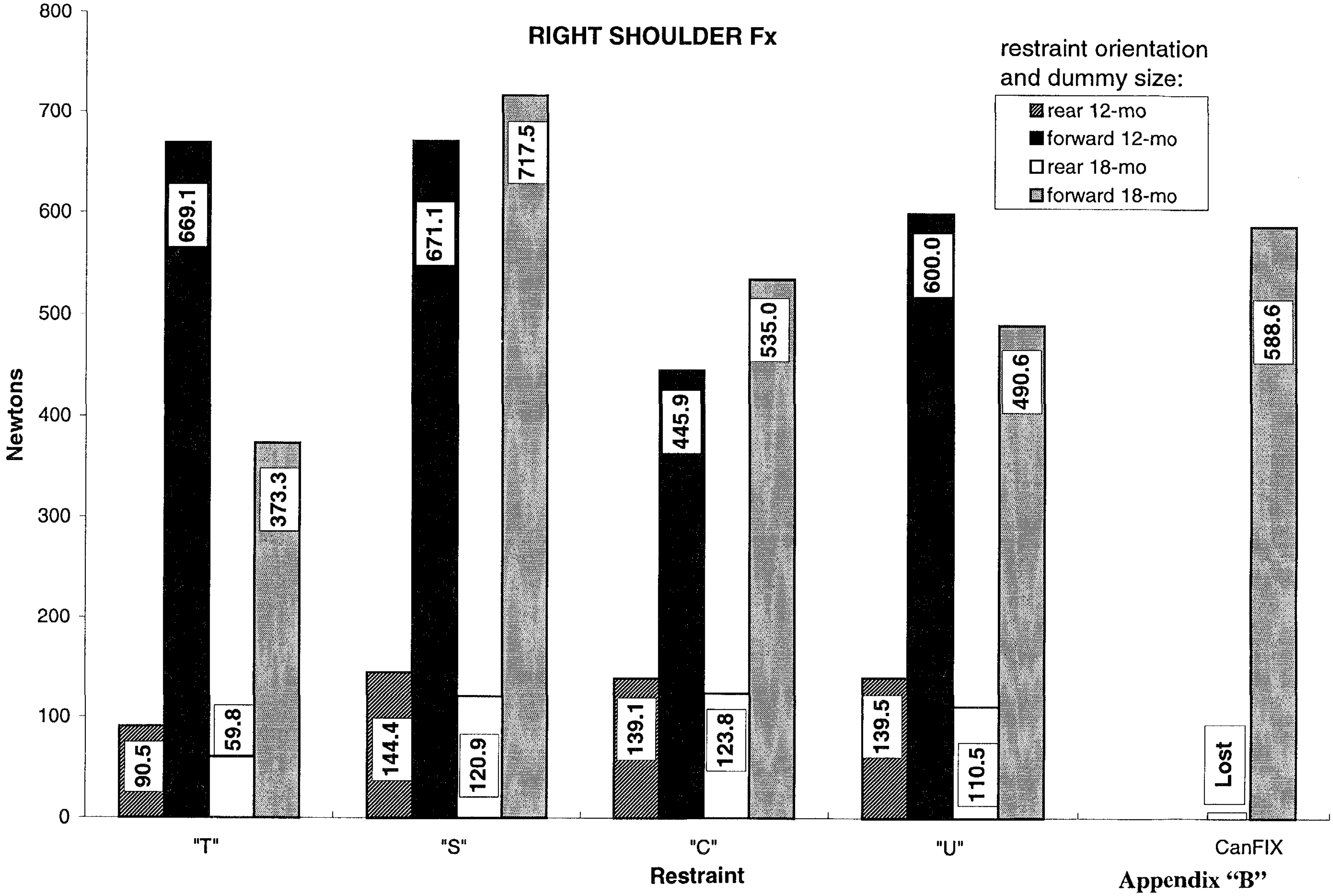

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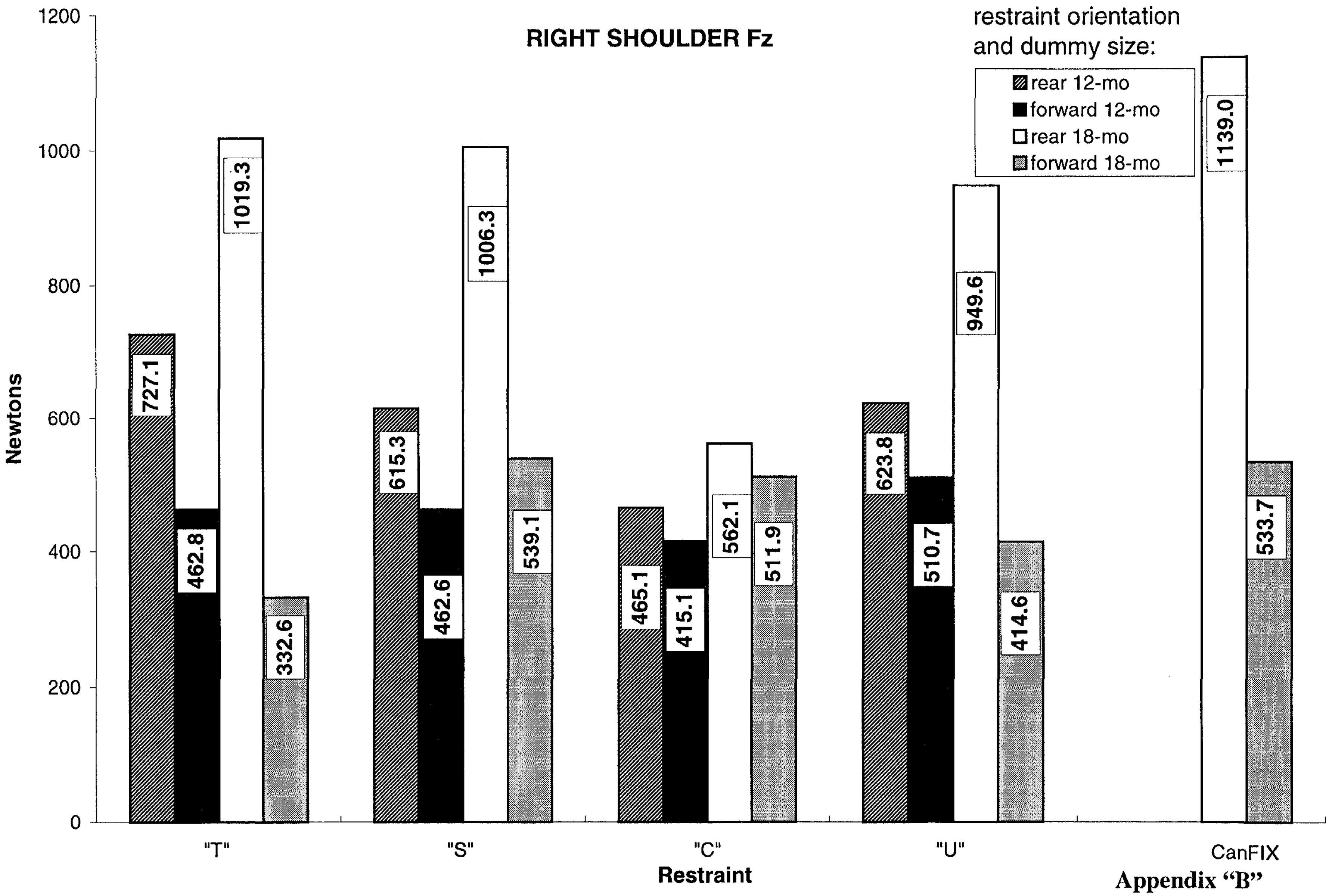

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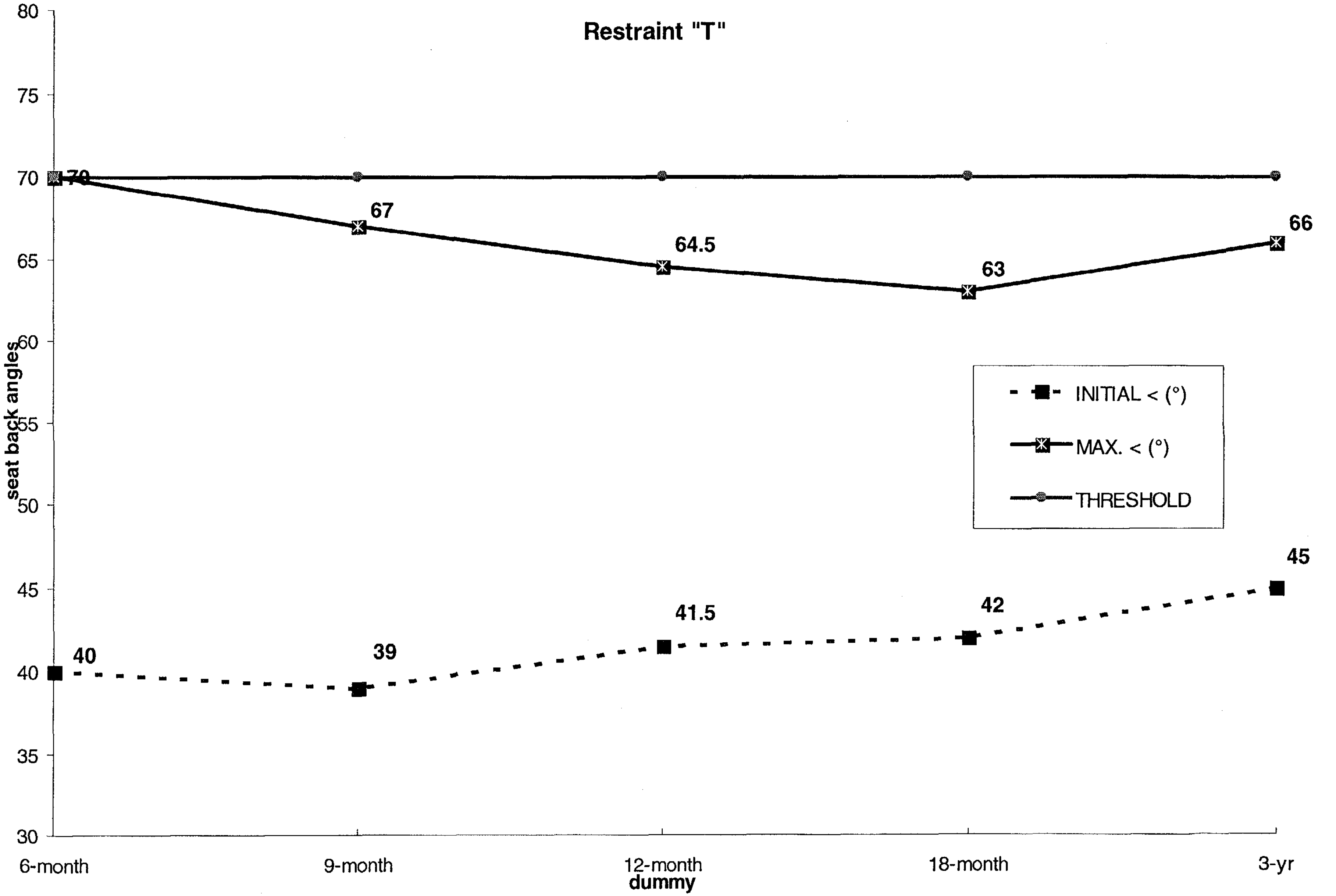

Appendix "C"

Figure "C-1"

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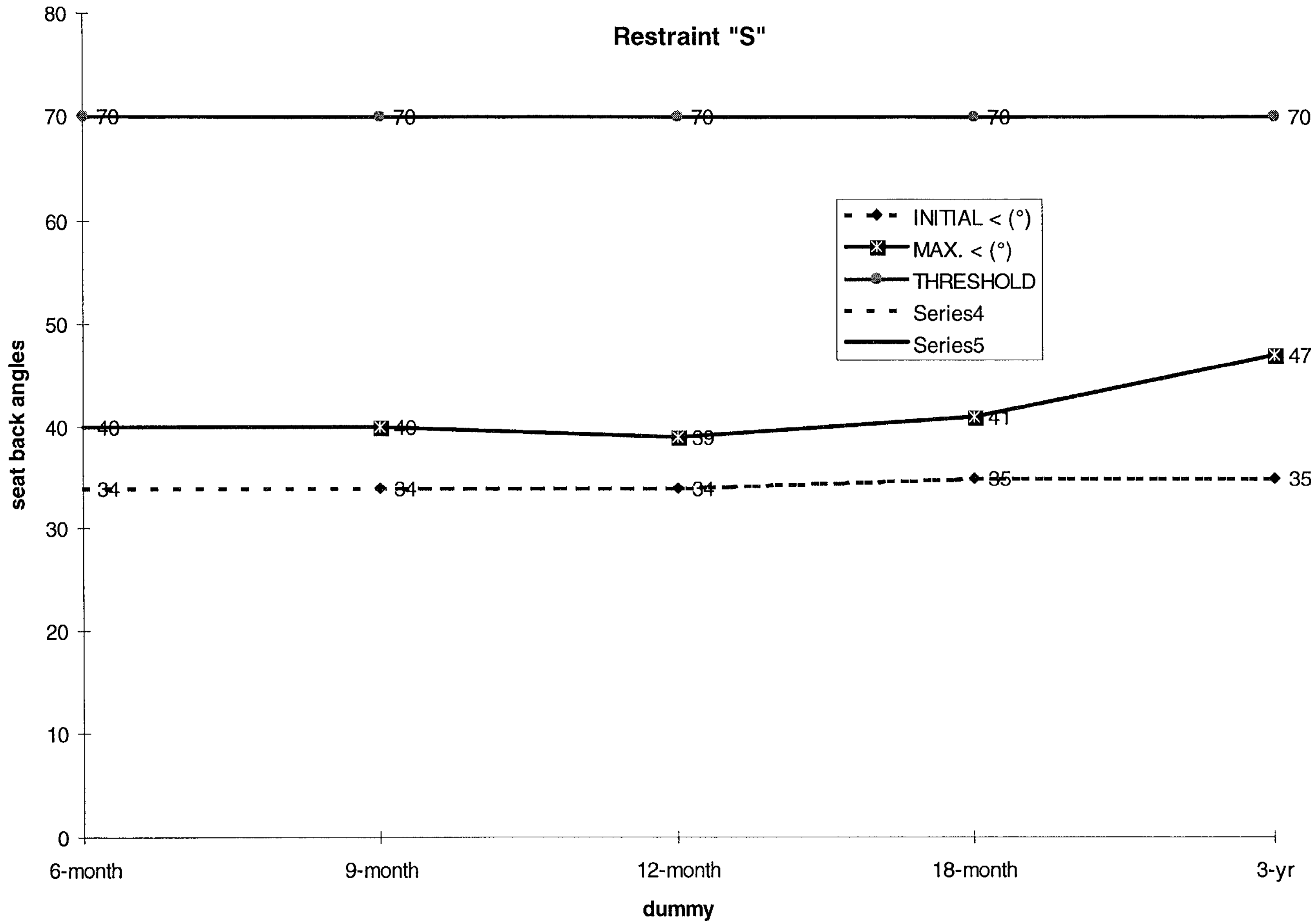

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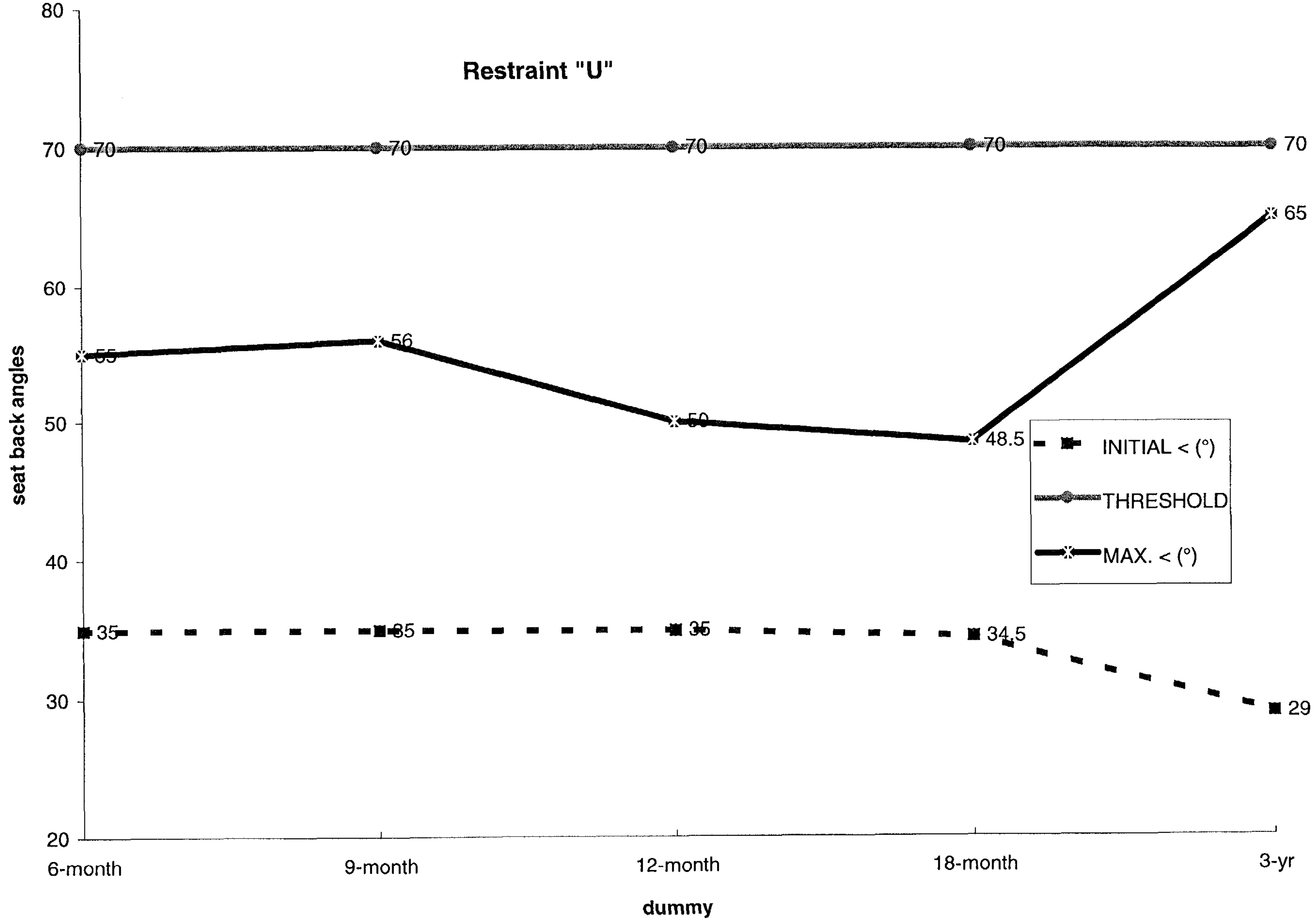

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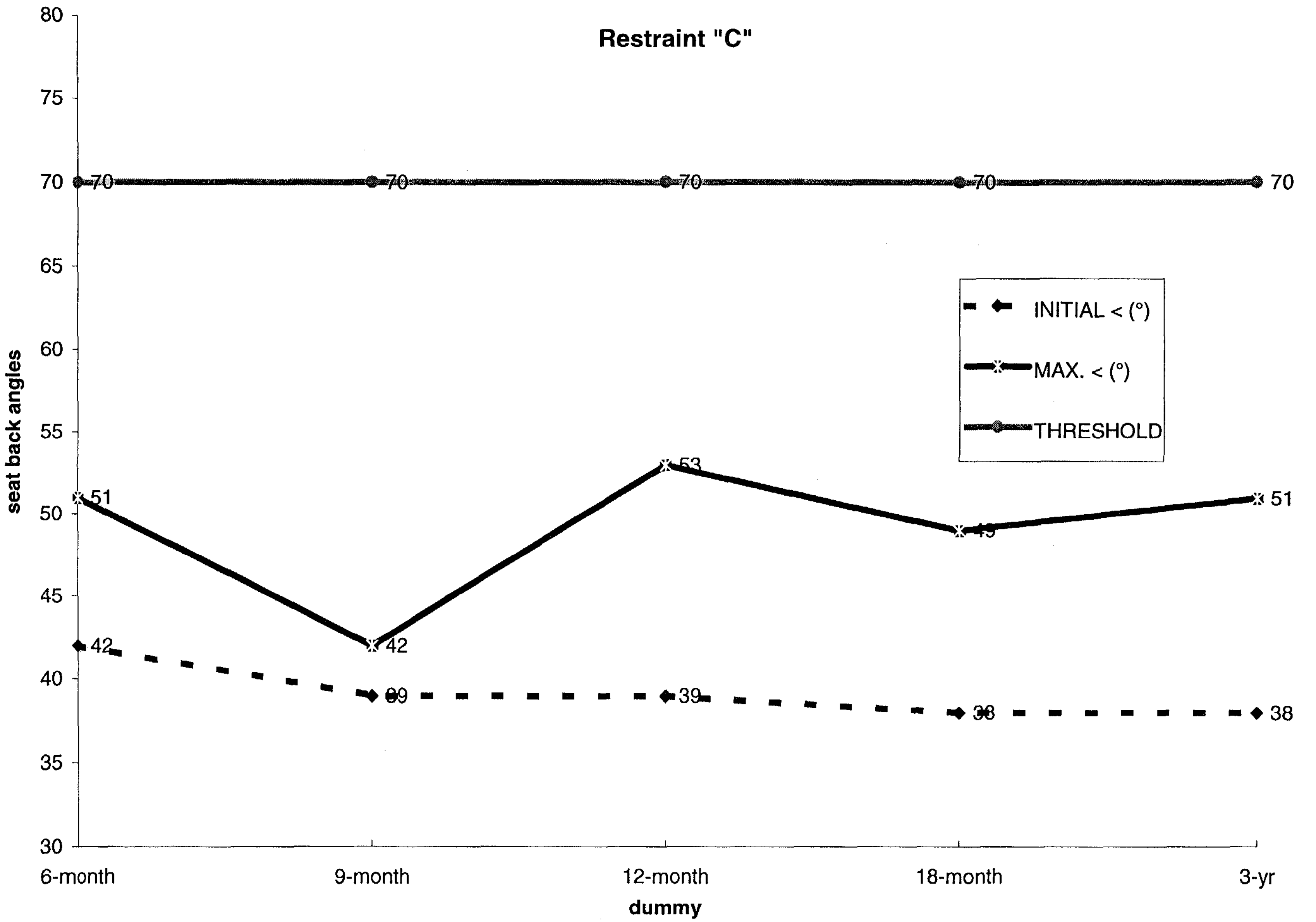

Appendix "C"

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