this study were presented in 2001 at the British Society for Rheumatology XVIIIth Annual General Meeting.

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(21)

模擬筋駆動型屍体実験装置を用いた全腰椎の筋負荷挙動

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要旨　腰椎の運動特性を理解するために，動作時の筋張力を再現できる模擬筋駆動型屍体実験装置を開発した．腹直筋，左右内・外腹斜筋，左右脊柱起立筋に模したステンレスワイヤ7本を屍体腰椎に取り付け，筋張力方向に牽引した．ワイヤ張力の制御には，ステッピングモータとロードセルで構成したサーボアクチュエータを用いた．筋張力は，腰椎の筋骨格靱帯モデルと実際の運動データから推定した．新鮮屍体腰椎2体に対し，前屈30°，後屈20°，側屈20°，回旋10°を行わせたところ，実運動と同等の動作を再現できた．また，前屈運動であっても腰椎形状の左右非対称性によって椎骨間に側屈運動が生じることがわかった．さらに，側屈運動ではL4−5で側屈方向が逆転した．回旋運動ではL1が最も大きくL2とL3が一体として動き，L5は回旋しなかった．また，回旋に随伴する側屈角度はL3で大きくなった．

キーワード：腰椎，屍体実験，筋張力負荷装置，腰椎運動，生体力学

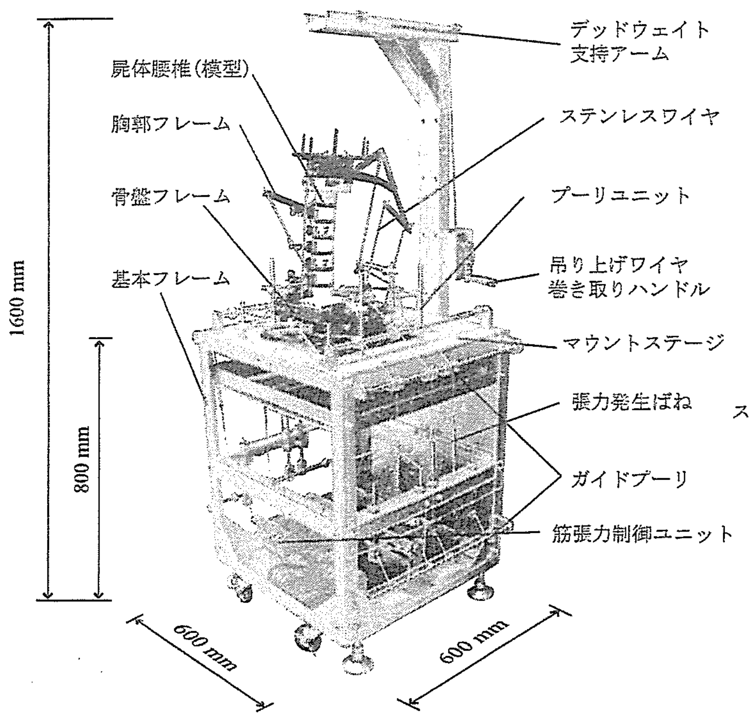
1．はじめに

腰痛や腰椎変形疾患などの治療法と予防法の確立には，腰椎の運動特性を知ることが基礎的課題になっている．

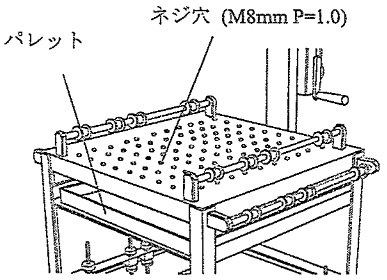
ヒトの腰椎は，複雑な形状を持つ骨と強い非線形性を示す軟部組織により構成される．このため，単純な動作であっても個々の椎骨は並進と回転運動が組み合わさった複合動作を起こし，その運動特性の理解は容易ではない．

腰椎の運動特性の研究手法には，生体計測[1]，屍体実験[2]，モデル解析[3]などがあるが，特に屍体実験は腰椎の運動を直接計測することが可能である点で，他の方法の信頼性評価にも用いられる．

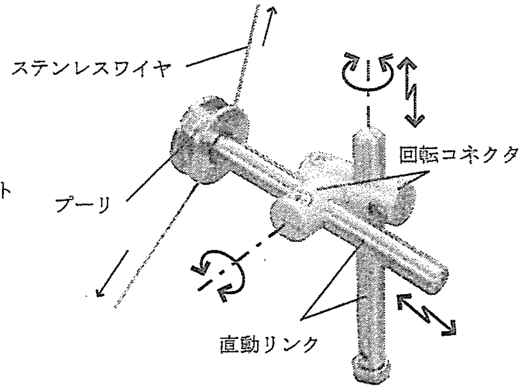
Panjabiら[2]は，力のモーメントを負荷して屍体全腰椎を屈曲させる荷重方法を提案した．この実験手法は，屍体腰椎を均一な曲げモーメント状態にできるため，実験者間の計測値の比較を容易にできる利点があり，荷重値[4]，外科手術法[5]，治療器具[6]ごとの椎骨間の可動域が比較されている．また，腰椎長軸方向への圧縮力を作用させる実験装置[7]も開発



(a)　模擬筋駆動型屍体実験装置



(b) マウントステージ



(c)　プーリユニット

図 1　模擬筋駆動型屍体実験装置

されたが，これらの単純負荷装置では，生体腰椎の運動特性を再現することはできない．

このため Wilke ら[8]は，多裂筋，腸肋筋，大腰筋の筋張力を空気圧アクチュエータで再現し，筋の組み合わせによる L4-5 間の相対角度および椎間板内圧の変化について報告した．しかしこの装置でも，筋張力を変化させて動作中の腰椎運動を観察するまでには至っていない．

生体腰椎の運動を屍体腰椎において再現するには，実際の筋配置方向に生体が発生する張力を時系列で与える必要がある．

本研究では，ステッピングモータとロードセルによりサーボアクチュエータを構成し，これを 8 台搭載した模擬筋駆動型屍体実験装置を開発した．筋張力の時系列変化は，筋骨格靱帯モデル[9]と実際に計測した前後屈，側屈，回旋時の生体運動データを用いて推定した．この筋張力を新鮮屍体腰椎 2 体に加え，腰椎挙動の計測を行った．

2．模擬筋駆動型屍体実験装置

2.1　模擬筋駆動型屍体実験装置の設計仕様

屍体実験装置の設計では，再現する筋数と最大筋張力が基本条件となる．

本研究では腰椎の主働筋でありモーメントアームが長い腹直筋，左右内・外腹斜筋，左右脊柱起立筋の 7 筋を模擬することとし，動作再現のための追加の可能性も残して 8 筋まで負荷できることにした．大腰筋も腰椎姿勢の安定化に寄与していると考えられているが[8]，粗大動作に対してはモーメントアームが小さいことと，その付着の再現が困難なことから，模擬は今後の課題とする．また，従来の屍体実験では損傷を防ぐために 10 Nm 程度の負荷が用いられていることから，筋のモーメントアームを平均 0.1 m と仮定して最大筋張力を 100 N とした．なお，この値は屍体腰椎の最大許容圧縮力[10]の 10 %(100 N) 程度になっている．さらに，同じく腰椎の損傷を防ぐために，張力は準静的に加えることとした．

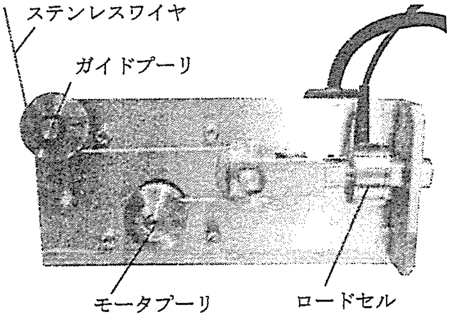
実験中には屍体腰椎の乾燥による変性を防ぐために生理食塩水を噴霧する。この腐食に耐えられるよう全構成部品をステンレス（SUS 303）で製作した.

2.2　装置の基本構造

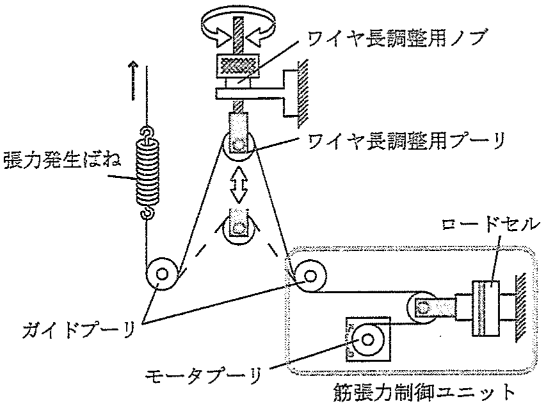
図1に模擬筋駆動型屍体実験装置を示す. 屍体実験装置は基本フレーム，デッドウェイト支持アーム，8台の筋張力制御ユニットで構成されている.

デッドウェイト支持アームは，過度の屈曲などによる屍体腰椎の損傷を避けるための安全装置であり，腰椎上部につけたワイヤの長さで可動域を制限することができる.

筋張力は図2に示す基本フレーム下部の筋張力制御ユニットと張力発生ばねにより発生され，ステンレスワイヤ（ϕ 1.0 mm）によって屍体腰椎に加えられる. 筋張力制御ユニットはステッピングモータとロードセルで構成される. ステッピングモータ軸のプーリに取り付けられたステンレスワイヤは，ロードセル先端に取り付けられたプーリとガイドプーリを介して基本フレーム外部に引き出され，基本フレーム側面の張力発生ばねに連結される. 筋張力は，モータでワイヤを巻き取ることにより，ばねを伸張させて発生する. これにより外乱による姿勢変化をばね力の変化で抑制できるため，屍体の損傷を避けることができる. なお，ワイヤ走行はロードセル先端のプーリで180度方向を変えるため，ロードセルには2倍の張力が加わる. ロードセルの検出値は制御用PC（Dimension 8250, DELL社）に入力し，PID制御にてステッピングモータの回転角度にフィードバックした.



(a) 筋張力制御ユニット(正面図)



(b) ワイヤ走行

図2　筋張力の発生と制御機構

発生した筋張力はステンレスワイヤの張力に置き換えて，筋付着相当位置に加えた. 付着部を再現するために，胸郭と骨盤を模擬したフレームを作成した. また筋張力の作用方向を再現するために，プーリを用いてワイヤ方向を調整できるようにした.

基本フレームの大きさはW 600×D 600×H 800 mm（デッドウェイト支持アームまで1600 mm）であり，全重量は約100 kgである. 基本フレームの上部はマウントステージとし，M8用ネジ穴を50 mm間隔の格子状に設けた. このネジ穴を利用して屍体腰椎とプーリユニットを取り付けることができる. プーリユニットは，筋張力の作用方向にワイヤの走行方向を一致させるために用いる. また，マウントステージの下には生理食塩水などを受けるパレットを取り付けた.

2.3　筋付着位置と胸郭・骨盤フレーム

筋の付着位置はStokesらによる報告[11]を参考に表1のように決定した. なお，前方をx，左方をy，頭方をz軸とし，胸郭の原点はT 12椎体重心，骨盤の原点は仙骨底中央とした.

表1　筋付着位置

	胸郭座標 [mm]			骨盤座標 [mm]		
	x	y	z	x	y	z
腹直筋	148	0	29	123	0	45
内腹斜筋(左)	71	129	-100	71	121	-25
内腹斜筋(右)	71	-129	-100	71	-121	-25
外腹斜筋(左)	-20	142	-60	109	114	-55
外腹斜筋(右)	-20	-142	-60	109	-114	-55
脊柱起立筋(左)	-40	20	-14	-48	40	-29
脊柱起立筋(右)	-40	-20	-14	-48	-40	-29

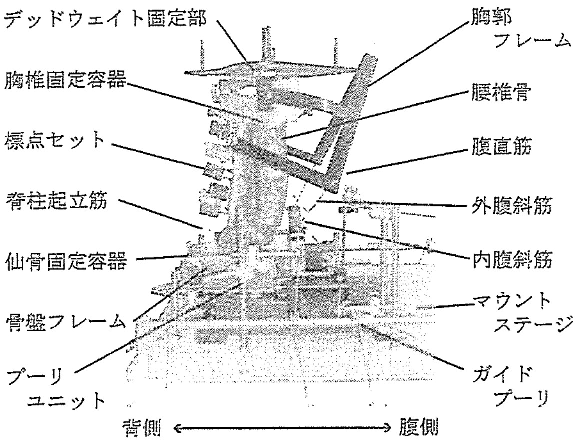


図3　筋走行の再現

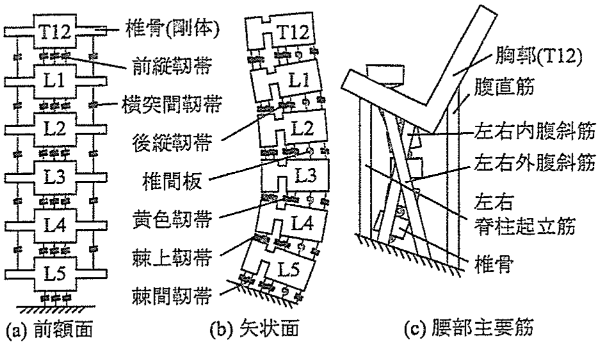


図4　腰椎筋骨格靱帯モデル

実験時の筋走行の様子を図3に示す．胸郭下端の形状を模した胸郭フレーム（幅284 mm，奥行き164 mm，高さ144 mm）の筋付着点にはワイヤ取り付け穴を設け，仙骨フレームの筋停止点にはワイヤ経由ガイドを取り付けた．この間を結ぶ各ワイヤは，マウントステージ上のプーリユニットにより張力発生ばねに導いた．

2.4　上半身重量と腹圧

上半身重量は，デッドウェイトとして常に腰椎を圧迫しているが，腰椎の剛性特性には影響しないと報告されている[12]．本研究では，装置で発揮する最大張力（100 N）に合わせ，上半身重量も比例的に減少させることとし，上半身の平均重量を25 kgと仮定して屍体実験時の上半身重量を2.5 kgとした．

また Chaffin[13]の腹圧推定式によれば，前屈30°のとき，腹圧は上半身の自重によるモーメントの約15％程度を支持している．しかし，本研究では，上半身重量を10％まで軽減したため，腹圧による支持は無視した．

2.5　筋張力負荷の推定

図4に，7筋，6椎骨，112靱帯および椎間板ばね要素からなる腰椎の筋骨格靱帯モデル[9]を示す．このモデルでは椎骨は剛体と仮定し，靱帯および椎間板は線形ばね要素でモデル化している．また，胸郭フレームも剛体として再現し，筋の付着部と走行を屍体実験と同様に設定した．姿勢は図4(c)に示す左右7筋の張力によって変えることができる．しかし6椎体それぞれが6自由度を持ち，かつ，ある姿勢をとる時の筋張力は冗長なため，計測した実際の姿勢変化を与え，最適化手法によって時々刻々の筋張力を求めた．

各椎骨には，椎体重心を原点，椎体前面側をx，左面側をy，上端面側をz軸とする椎骨座標系を固定し，椎骨間の相対運動は下椎骨に対して定義した．胸郭の姿勢を代表するT12は，初期姿勢において前方をx，左方をy，頭方をz軸とした．

最適化計算においては，拮抗筋張力が大きくなりすぎないように，筋応力を探索変数とし，最適化は次式を最小化するように行った．

$$\alpha(u-u')^2+\beta\Sigma\sigma^3_{\mathrm{muscle}} \qquad (1)$$

ここでuは目的とするT12の運動角度［deg］，u'は再現する運動角度［deg］，σ_{muscle}は筋応力［N/mm^2］，Σは7つの筋の総和，αおよびβは重み係数であり，式(1)の第1項と第2項の数値の大きさが同等になるように$\alpha=100$，$\beta=1$とした．この条件で，最終的な運動角度差は0.01°以下となる．

本研究では，まず動作中の腰椎姿勢を計測し，時々刻々の腰椎姿勢と筋骨格靱帯モデルから動作中の7筋の筋張力を推定した．この推定した筋張力を模擬筋駆動型屍体実験装置で時系列に発生させることで，屍体腰椎に生体動作を再現させた．

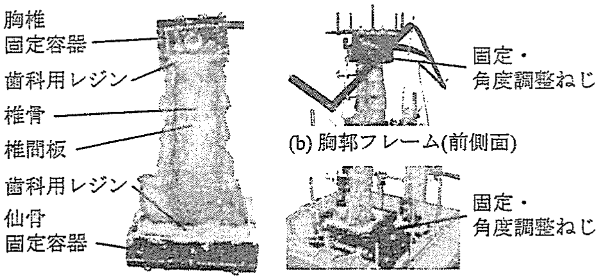
3．屍体実験方法

3.1　屍体の前処理

慶應義塾大学医学部解剖学教室に献体された新鮮屍体2体から，死後24時間以内に全腰椎を摘出し

表 2　標本の形態情報

	標本1 [mm]					標本2 [mm]				
	椎体		椎間板			椎体		椎間板		
	高さ	横径	前側	左側	右側	高さ	横径	前側	左側	右側
L1	24.0	42.2	8.6	8.4	7.3	19.6	34.9	9.7	6.8	6.3
L2	24.8	43.2	11.2	10.9	9.6	20.9	37.3	10.4	7.1	7.4
L3	25.2	43.4	12.3	12.1	10.8	22.1	39.8	12.5	8.0	7.8
L4	25.4	48.2	15.6	15.0	13.2	23.7	39.4	14.6	10.9	10.7
L5	22.3	52.4	17.2	12.5	11.7	20.2	40.1	15.2	11.4	12.2
S	-	-				-	-			



(a) 屍体腰椎(正面図)　(b) 胸郭フレーム(前側面)　(c) 仙骨フレーム(後側面)

図 5　屍体腰椎の固定方法

た．T 11 椎体部から S 2 までを一塊として離断し，T11 および T12 に付着する肋骨は基底部にて切断した．摘出した標本はただちに冷凍保存し，実験開始の 24 時間前より室温にて自然解凍した．解凍後，軟 X 線発生装置（SOFTEX type CMB-2，ソフテックス社）を用いて前額面と矢状面の撮影を行った．レントゲン画像と実際の標本を基に，脊椎専門医が標本に変性・変形がないことを確認した．標本の形態情報として，椎間板と椎体寸法を表 2 示す．

屍体腰椎と胸郭および骨盤フレームの固定方法を図 5 に示す．屍体腰椎の T11，T12 横突起および S 2 を切断し，腰椎を逆さにして T12 を枡形の胸椎固定容器に入れ，歯科用レジン（OSTRON II，GC 社）を流し込んだ．固定容器と屍体腰椎とが一体となるように，完全に固まるまで手で保持した．固定後，再び元の姿勢に戻し，S1 も同様に仙骨固定容器に入れ，歯科用レジンにて同様に固定した．

また標点セットを取り付けるため，各棘突起に後方から前方に向けて，電動ドリルを用いてキルシュナ鋼線（ϕ 2 mm）を 2 本ずつ挿入した．

この後，仙骨固定容器と胸椎固定容器にそれぞれ骨盤フレームと胸郭フレームを取り付け，マウントステージ上に骨盤フレームをねじ固定した．また，前額面において腰椎に傾きが生じないように，矢状面では，L 3 の上端面が立位時と同様に水平になるように固定容器と各フレームの取り付け角度を調整した．

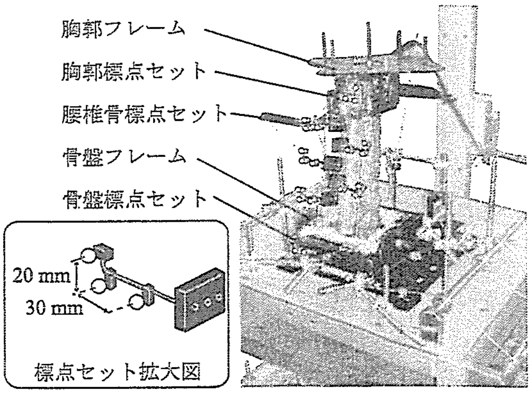


図 6　標点セットの設定

最後に胸郭フレームの筋付着穴から経由プーリに沿ってステンレスワイヤを走行させ，側面の張力発生ばねに取り付けた．

3.2　運動計測

図 6 に示す各椎骨に取り付けた標点セットの位置を，3 次元空間計測装置（ProReflex，Qualysis 社）の 3 台のカメラを用いて 100 Hz で計測した．標点セットに対して各椎骨の解剖学的特徴点をあらかじめ計測することで，椎骨に対する標点セットの相対位置を求めた．計測視野 600×600 mm² での計測精度は，回転 0.5°，並進 0.8 mm であった．

男性被検者（身長 170 cm，体重 65 kg）1 名に，日常の基本動作である前屈 30°，後屈 20°，側屈 20°，回旋 10° に到達するまでの約 5 秒間の準静的運動を行わせ，骨盤に対する胸郭角度の時系列変化を計測した．

また屍体実験では，推定した筋張力を負荷して前後屈，左右側屈，左右回旋を行わせ，それぞれ 2 回ずつ計測した．各実験の間では，負荷した全ての筋張力を取り除き，腰椎が静止していることを確認してから，次の運動の筋張力を加えた．

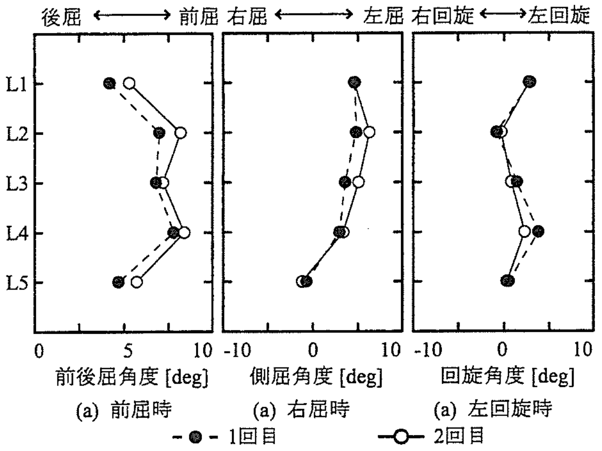
4．結果および考察

4.1　実験の再現性

実験の再現性を確認するために，同じ筋張力を負荷した時の主運動に関する椎骨間の相対角度を比較した．図7に比較の一例を示す．右屈，左回旋運動においては2回の実験計測で大きな角度差は見られなかったが，前屈については2回目の方が大きく傾いた．しかし，胸郭の絶対角度28.7°に対して，2回の差は1.3°と十分小さい．この再現性は，筋張力負荷実験によっても標本腰椎が損傷していないことを示しており，実験後に行った医師の確認でも，変性や損傷は確認されなかった．

4.2　運動時の筋張力

筋骨格靭帯モデルにより推定した筋張力と，装置が発生した張力を図8，9，10に示す．張力発生指令後0〜5秒までは微少な調整張力を与えて腰椎姿



(a) 前屈時　(a) 右屈時　(a) 左回旋時

図7　可動域の再現性

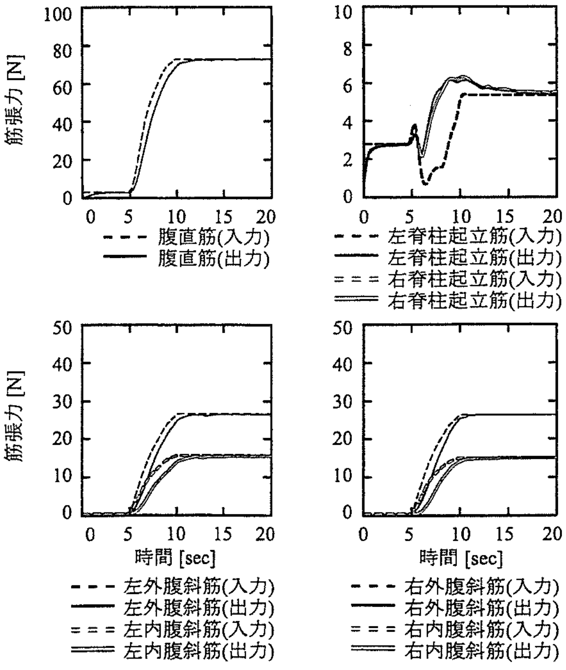


図8　筋張力の変化（前屈30°）

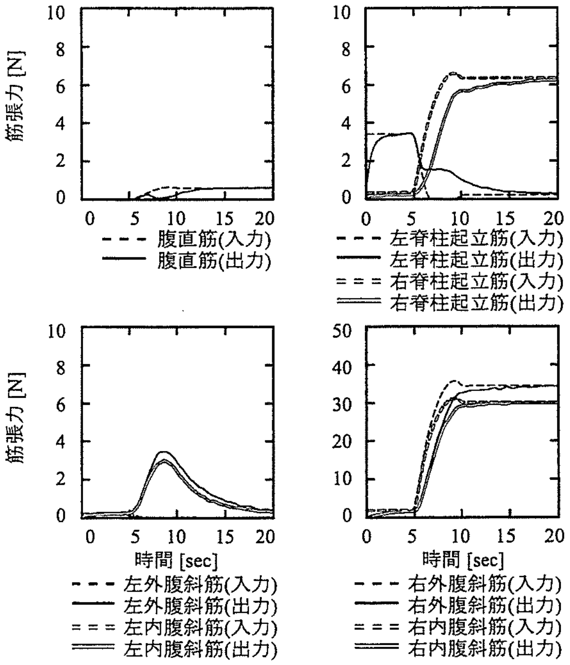


図9　筋張力の変化（右側屈20°）

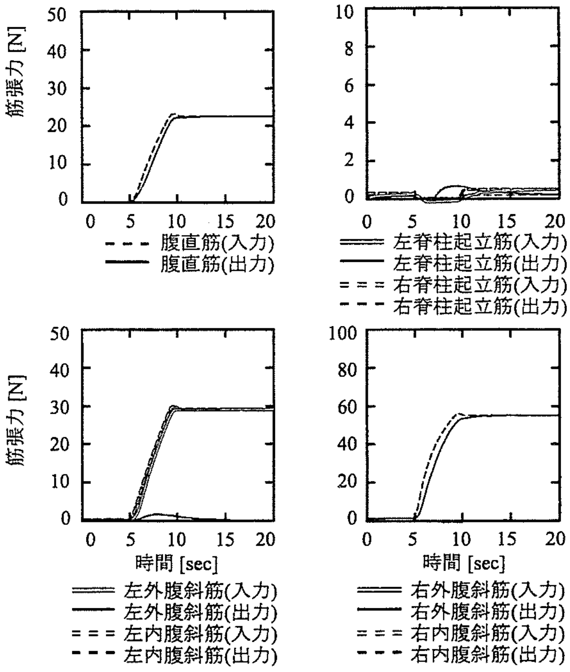


図10　筋張力の変化（左回旋10°）

勢を安定化させ，この後5秒内で筋張力を準静的に加えた．また，残りの10秒間は腰椎の運動が収束するのに必要な時間とした．なお，前後屈運動では，左右対称に筋張力を加えた．

筋張力の目標値に対して張力の出力は1.5秒程度遅れるが，動作速度に比べて無視できる．また20秒後の張力値は両者でほぼ一致しており，最終安定姿勢には影響しない．

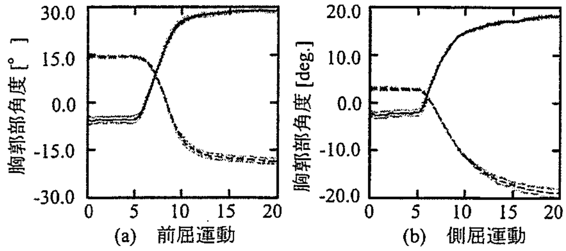
4.3　目標運動の再現

図11に，目標運動を行わせた時の胸郭部の角度変化量を示す．ここで0°は初期状態である．各運動において，筋張力が増加する5秒から胸郭角度が増加し，10秒付近でほぼ収束した．収束角度は，2回の平均で前屈角度が28.7°（目標30°），後屈角度が18.7°（20°），左右側屈角度が18.5°（20°），左右回旋角度が8.8°（10°）であり，2体の運動特性に大きな違いはなかった．この結果は，7筋で全ての方向の運動を実現でき，筋張力，筋走行，上半身重量が適切に設定されていることを示している．

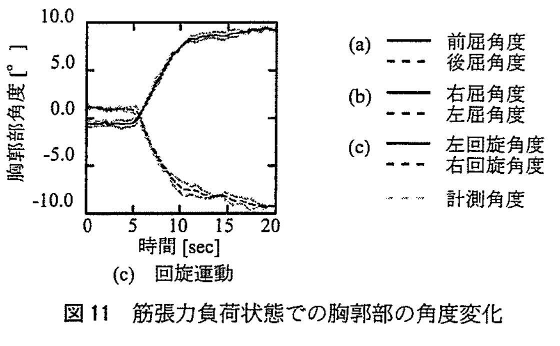
屍体実験装置が目的とする筋張力を発生したにもかかわらず，姿勢角度が目標の90％までしか達しなかったのは，筋骨格靱帯モデルの弾性特性が実験した屍体腰椎よりも小さく，推定筋張力が小さかったためと考えられる．この差は，運動結果を筋骨格靱帯モデルにフィードバックすることで容易に調整できるが，本実験では角度到達が目的ではないために，あえて調整は行わなかった．

また，腰椎にはニュートラルゾーンと呼ばれる軽荷重で大きく動作する範囲が存在[2,4]するため，荷重を取り除いただけでは必ずしも初期姿勢に戻らない．本実験においても，各運動後には胸郭角度が初期状態に戻らなかった．特に前屈と後屈運動では，側屈と回旋運動に比べてより大きな屈曲角度が残った．このため，前後屈終了後および側屈終了後に強制的に初期姿勢に戻した．

なお，側屈と回旋では運動開始時の角度はほぼ左右対称であった．このことから，2体の標本腰椎に

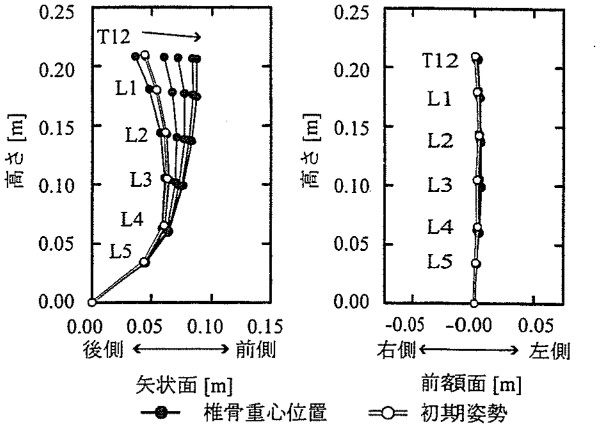


(a)　前屈運動　(b)　側屈運動

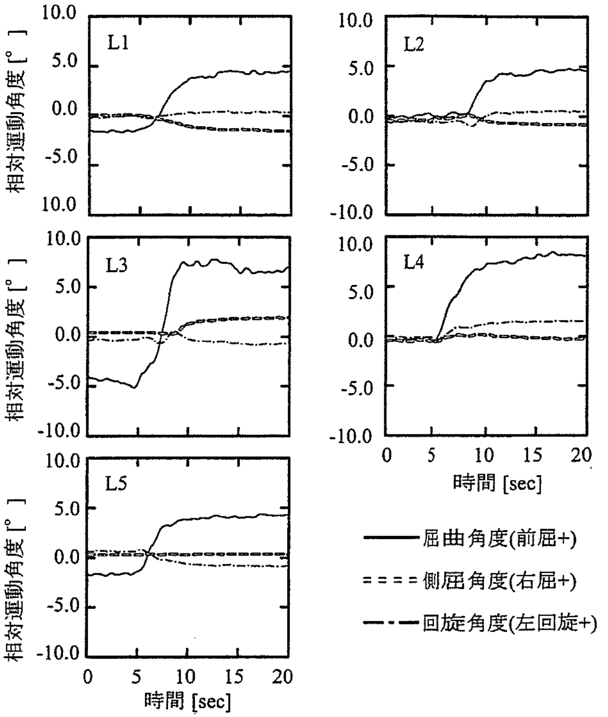


(c)　回旋運動

図11　筋張力負荷状態での胸郭部の角度変化

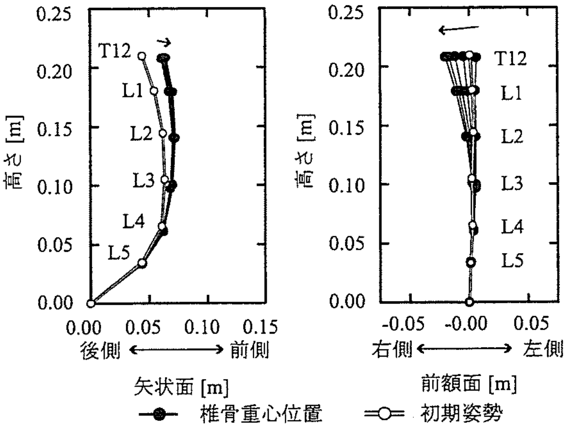


(a) 腰椎姿勢

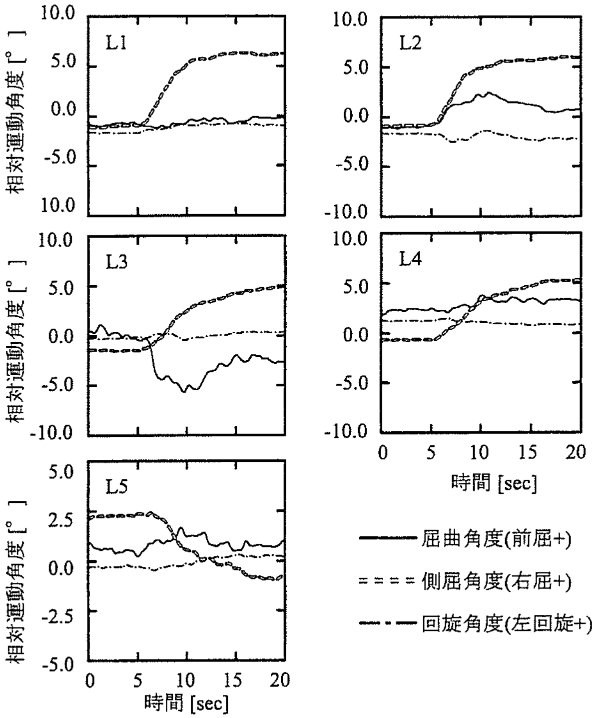


(b) 椎骨間の角度変化量

図12　腰椎の姿勢変化（前屈30°）

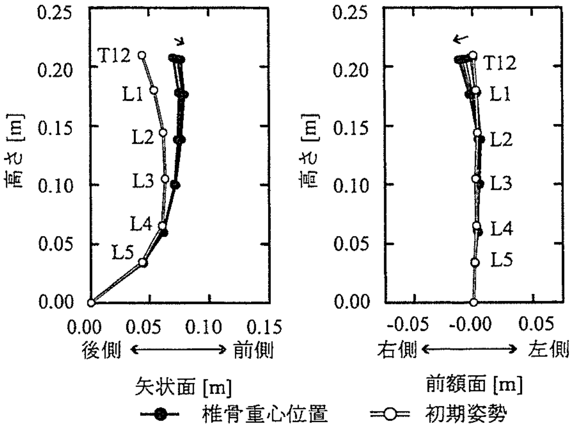


(a) 腰椎姿勢

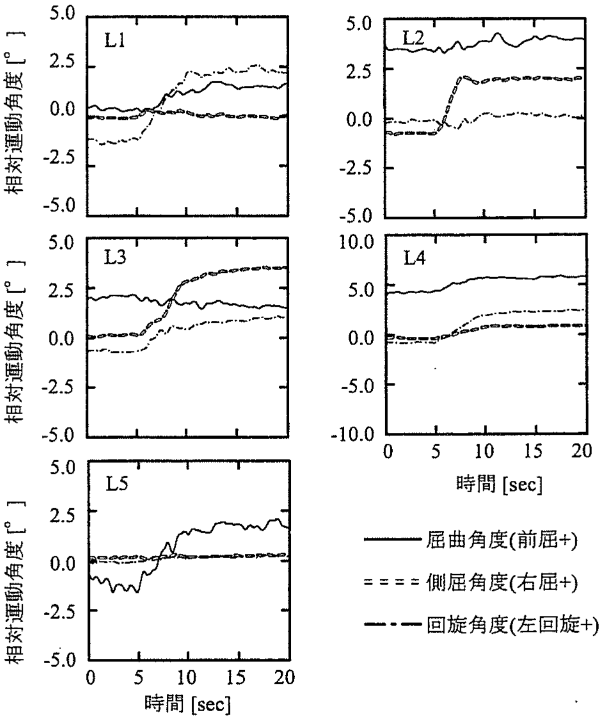


(b) 椎骨間の角度変化量

図 13　腰椎の姿勢変化（右側屈 20°）



(a) 腰椎姿勢



(b) 椎骨間の角度変化量

図 14　腰椎の姿勢変化（左回旋 10°）

は運動特性に左右差はないと考えられる．

4.4　腰椎の姿勢変化と椎骨間の運動

筋張力を負荷した時の腰椎の姿勢変化と椎骨間の相対角度変化を図 12，13，14 に示す．腰椎の姿勢変化は各椎骨の重心位置を結んだものであり，5 秒から 10 秒まで 1 秒ごとに表示してある．また各椎骨の座標定義は，筋張力の推定に用いた腰椎の筋骨格靱帯モデルと同様である．

図 12 に示す前屈運動では，負荷した張力は左右対称であるため，腰椎はほぼ矢状面内で運動が生じている．一方，椎骨間の運動では L1，L2 においてやや側屈運動が生じており，L3 では逆の側屈運動が生じた．本実験で用いた屍体腰椎は，前額面において L 3 が左側に 3 mm 程度凸となる緩やかな側弯形状を示していた．筋張力負荷時には腰椎を長軸方向へ圧縮することになるため，弯曲が強まるように圧縮され，これに伴い L2-L3 間で側屈運動が生じたと考えられる．

図 13 に示す右屈運動では，初期姿勢に比べやや前屈位を保ちながら運動が生じていた．椎骨間の相対運動は，L1-4 では側屈角度が増加したが，L5 で

は反対側への運動を示した．左屈時にも L5 は上位椎骨と反対側へ運動していたことから，筋張力を負荷した側屈運動では全ての椎骨が同側に回転するわけではないことがわかる．

回旋運動では，図 14 に示すように前屈姿勢を保ちながら回旋と反対側への側屈が生じた．回旋の主働筋である外腹斜筋と内腹斜筋は筋走行が異なるため，これらの筋張力によるモーメントの非回旋成分の差が，前屈と側屈運動を行わせたと考えられる．

椎骨間の運動に注目すると，L2 と L5 ではほとんど回旋しなかった．これに対し，回旋に伴う側屈運動は L2，L3，L4 で生じており L3 が最も側屈角度が大きかった．椎間板はくさび型であるため，回旋によってくさびの向きが変わり側屈を起こすと考えられる．

5．おわりに

本研究では，生体内に近い力学条件を再現するために，模擬筋駆動型屍体実験装置を開発して屍体実験を行った．腰部主働筋として 7 筋を再現し，筋骨格靱帯モデルを用いて推定した動作時の時系列筋張力データを新鮮屍体腰椎に作用させた．この結果，屍体腰椎にほぼ目標姿勢をとらせることができ，本屍体実験装置で生体の筋張力負荷状態を模擬できていることがわかった．

また，この時の椎骨間の相対角度の変化から，前屈運動であっても腰椎形状のわずかな左右非対称性によって側屈運動を生じることがわかった．側屈運動では L4 と L5 で側屈方向が逆転し，回旋運動では L1 が最も大きく，L2 と L3 は一体として動き，L5 では回旋角度が生じていない．また，回旋に随伴する側屈運動は L 3 で大きくなった．

本研究では大腰筋と腹圧を再現していないため，今後は筋骨格靱帯モデルを活用してその影響を考察する予定である．

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Movements of the Whole Lumbar Spine Using Muscle Active Simulator

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Abstract A muscle active simulator for cadaveric lumbar experiments was developed. This simulator can generate wire tensions as the complex and continuous muscle forces of 7 muscles in lumbar spine; m. rectus abdominis, m. obliquus internus abdominis, m. obliquus externus abdominis and m. erector spinae. The wire tensions were controlled by servo actuators consisting of stepper motors and loadcells. The muscle tensions were obtained by a musculoskeletal lumboligamentous model and actual motion data. The maximum tension was limited to 100 N to avoid damaging cadavers. Under the muscle tensions of the flexion 30 [deg], the extension 20 [deg], the lateral bending 20 [deg] and the axial rotation 10 [deg], the motions of two fresh cadaveric lumbar spines were almost similar to the actual motion. The lumbar spine bent laterally even in the flexion motion because of the asymmetry spinal shape. When the lumbar spines bent laterally, L 5 vertebra bent reversely. In the axial rotation, L 1 rotated the most. L 2-L 3 moved as one unit, but L 5 fixed on the sacrum and L 3 bent laterally because of the wedge shape of intervertebral discs.

Key Words: Whole lumbar spine, Cadaver experiments, Muscle simulator, Lumbar motion, Biomechanics

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Lateral Translation of the Lumbar Spine: In Vitro Biomechanical Study

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A biomechanical study of lateral translation in lumbar spine with human cadavers was performed in order to explore the direction of the force increasing lateral translation and the contributions of discs and facet joints to lateral translation. Whole lumbar spines from 12 fresh cadavers were attached to a specially designed loading apparatus whose five cables simulated the muscles of the trunk without restricting natural movement. Three-dimensional positions of each vertebra were recorded with position-sensitive detectors. Force in the anterolateral direction increased the lateral translation more than force in the posterolateral direction. Lateral translation was increased to a significantly greater extent when the facet joints were removed than when the discs were removed at L4-5 at the levels of shear loading applied in this study.

***Key Words*:** cadaver, scoliosis, degeneration

Degenerative lumbar scoliosis is becoming a more frequent problem in the elderly population (Epstein, Epstein, & Jones, 1979; Robin, Span, Steinberg, Makin, & Menczel, 1982; San Martino, D'Andria, & San Martino, 1983; Simmons & Simmons, 1992). Lateral listhesis of the lumbar vertebrae is often present in patients with degenerative lumbar scoliosis and can complicate their management (Grubb, Lipscomb, & Coonrad, 1988; Piat, Laredo, & Tassin, 1995). Radiculopathy or neurogenic deficits caused by lateral listhesis are common complaints of patients with degenerative lumbar scoliosis. Recently, Liu et al. (2003) discovered that the lateral listhesis in patients with degenerative lumbar scoliosis in which the L3 or L4 root on the concave side of the curve was affected were larger than in patients in which the L5 or S1 root on the convex side was compressed.

There is controversy regarding the management of degenerative lumbar scoliosis, especially the necessity of fusion surgery (Daffner & Vaccaro, 2003; Grubb, Lipscomb, & Suh, 1994; Gupta, 2003). Tribus (2003) considered posterior fusion to be reasonable in a patient with lateral listhesis > 5 mm.

Lateral listhesis is also recognized as an indicator of segmental instability of the lumbar spine and is one of the risk factors related to the progression of scoliosis (Kirkaldy-Willis & Farfan, 1982; Korovessis, Piperos, Sidiropoulos, & Dimas, 1994; Krismer et al., 2000; Nachemson, 1985; Sapkas et al., 1996). Radiological studies have suggested a relationship between loss of lordosis and lateral listhesis. In a study by Pritchett and Bortel (1993) of 200 consecutive patients, 171 had less lordosis than normal, and lateral listhesis ≥ 6 mm was one of the important predictive factors for curve progression, as was a Cobb angle ≥ 30°. Grubb et al. (1992) described 17 of 55 patients with degenerative scoliosis (31%) as having lumbar lordosis ≤ 30°, while 80% had lateral listhesis ≥ 5 mm, predominantly at the L3 and L4 levels.

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Although lateral listhesis in the analysis of roentgenograms is different from the pure lateral translation because horizontal rotation of vertebrae affects roentgenograms (Coleman, Harrison, & Bernard, 2001), a biomechanical experiment to investigate the direction of the force increasing lateral translation revealed the source of lateral listhesis in degenerative lumbar scoliosis. However, no previous biomechanical studies have focused on the details of the relationship between the direction of force and lateral translation.

Spinal motion at each level is regulated by bilateral facet joints and the intervertebral discs. Facet joint laxity and degeneration of the discs are thought to be involved in lateral translation. However, no causal relationship has been established between facet joints or discs and increased lateral translation. The current study was designed to explore the direction of the force increasing lateral translation and the contributions of discs and facet joints to lateral listhesis in vitro.

Methods

Whole lumbar spines, from the T12 vertebra to the sacrum, were procured from 12 fresh cadavers. The ages ranged from 60 to 85 years (mean = 76 years) and the male-female ratio was 6:6.

T12 vertebrae were sectioned at the level of the superior surface of the vertebral body. The sacrum was sectioned at 5 cm below the L5-S1 disc in the transverse plane. All ligaments, facet joints, and discs were left intact. The iliolumbar ligaments and the intertransverse process ligaments were also preserved bilaterally. The specimens were examined radiographically. No compression fractures or osteophytes, of the 3rd or 4th degree based on Nathan's (1962) method, were recognized. Neither slipping nor lateral listhesis was detected. The specimens were stored frozen at –20 °C, then thawed at room temperature for 24 hours before testing. For rigid fixation of the specimen, muscle and fat were removed and 2.0 mm diameter Kirschner wires were inserted into the T12 vertebra and the sacrum.

In order to confirm that translation or angulation occurred when the human lumbar spine was bent laterally, a natural bending force was loaded onto the specimen. Thus, a loading apparatus was specially designed and natural lateral bending motion of the specimen was reproduced by a pulley system (Figure 1). Five cables served as the *M. obliquus externus abdominis*, *M. obliquus internus abdominis*, and the back muscles, which were attached to an aluminum plate imitating the lower level of the thoracic cage at the points measured in an actual human skeleton. Two cables pulling the specimen simulated the *M. obliquus externus abdominis*, producing the lateral bending and anterior flexion (LAF) at the same time. The other two cables simulated the *M. obliquus internus abdominis*, creating the traction for the lateral bending and posterior flexion (LPF) simultaneously.

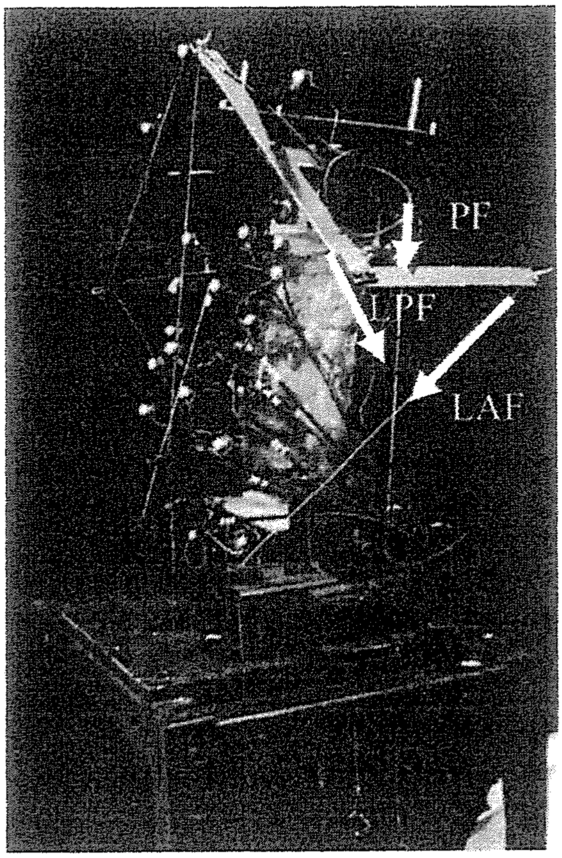


Figure 1 – The loading apparatus, designed for natural movement of the lumbar spine, has 5 cables that pull the headpiece attached to the T12 vertebra in different directions with a pulley system. Two cables pull the specimen producing the lateral bending and anterior flexion (LAF) at the same time. Two other cables create traction for lateral bending and posterior flexion (LPF). The remaining cable produces posterior flexion (PF). Three LEDs were attached to the anterior side of each vertebral body and the 3D positions of each vertebra were recorded with two position-sensitive detectors.

When the specimen was pulled in the LAF or LPF direction, it showed anterior or posterior bending motion as well as a lateral bending motion, which enabled us to investigate the influences of forces in the anterior and posterior directions on lateral translation of the lumbar spine. The remaining cable was for posterior flexion (PF) representing the back muscles. A specimen was attached to each part of the device using a polyester resin. First, the apparatus was modified to assure that the specimen was placed straight in the coronal view and that the superior aspects of the L4 vertebra was situated parallel to the horizontal line as viewed from the side.

To measure the position of each vertebra, we attached three LEDs to the anterior side of each vertebral body. Three-dimensional positions of each vertebra were recorded 200 times during a 2-second period with two PSD (position sensitive detectors, PSS-3570, Hamamatsu Photonics, Hamamatsu City, Japan). The measurement error of the PSDs was 0.64 mm according to the measurements in the previous experiment. We constructed the metal frame on which 16 LEDs were placed. The position of the each LED was accurately measured with a 3D digitizer (Micro-scribe 3D, Immersion Corp., San Jose, CA). Before starting the test, we measured 3D positions of the bilateral transverse processes and the upper anterior position of the vertebral body.

The upper portion of the loading apparatus, which weighed 1000 grams, had a preload effect on the specimen. In the preliminary experiment, 500-g, 1000-g, and 1500-g weights were applied to each cable attached to a new specimen. The specimens did not move sufficiently with the 500-g weight but did with 1000 g. Specimens were damaged in 1500-g weight loading. Accordingly, 1000 g was loaded onto each cable in this series of studies.

The first experiment was carried out to determine which direction of force increases lateral translation, LAF or LPF. After placing the specimen in the apparatus as described above, we loaded a 1000-g weight in a predetermined order: left side of the LAF cable, right LAF, left LPF, and finally the right LPF, with 30 seconds of creep at each loading step. Each specimen was subjected to the same series of tests three times.

Three-dimensional positions of the bilateral transverse processes and the upper anterior portion of each vertebral body were calculated from the measured LED positions using software specially designed to make the calculations. The origin of axes of each vertebra was defined as the median point of the bilateral transverse processes. The X axis on the horizontal plane was defined as passing through the bilateral transverse processes. The Z axis was defined as the line from the origin to the upper anterior portion of each vertebral body. The lateral translation was defined as the movement of the origin along the X axis. The lateral flexion angle was determined by the rotation around the Z axis, and the rotation angle was the rotation around the Y axis (Figure 2). The range of motion was defined as the absolute value of the remainder from the values when the weight was loaded onto the left cable to the values of the right cable.

A further experiment using 6 specimens was performed in order to investigate the contributions of facet joints and intervertebral discs to lateral translation. After the previous series of studies were done, a 1000-g weight was applied to the PF cable to prevent extreme anterior flexion of the specimen. Then a 1000-g weight was loaded onto the cable in the LAF direction, as in the previous study. For three specimens (Group A), the experiment was repeated after the intervertebral discs at L2-3, L3-4, L4-5, and L5-S had been removed (Step 1). Subsequently, the experiment was repeated after bilateral facetectomy at L2-3, L3-4, L4-5, and L5-S (Step 2). The Group B specimens were sectioned conversely, after removing the bilateral facet joints (Step 1). Then the intervertebral discs were removed (Step 2). To protect the anterior longitudinal ligament, we excised the discs from the lateral sides of the intervertebral spaces with scalpel and surgical puncher. The entire laboratory procedure was performed on each specimen and required no more than 6 hours.

A set of 200 data points was obtained in one series of tests, and after three series of tests had been performed, the average values of all 600 data points were adopted. The significance of the mean difference among L2-3, L3-4, L4-5, and L5-S was examined by ANOVA and the Scheffé test as a post hoc test, while a paired Student's *t*-test was used to determine the significance of the mean difference between the LAF and LPF direction forces.

Taking the range of motion at Step 2 into consideration, we used repeated-measures ANOVA to analyze the pattern difference between Groups A and B statistically, with the aim of evaluating the

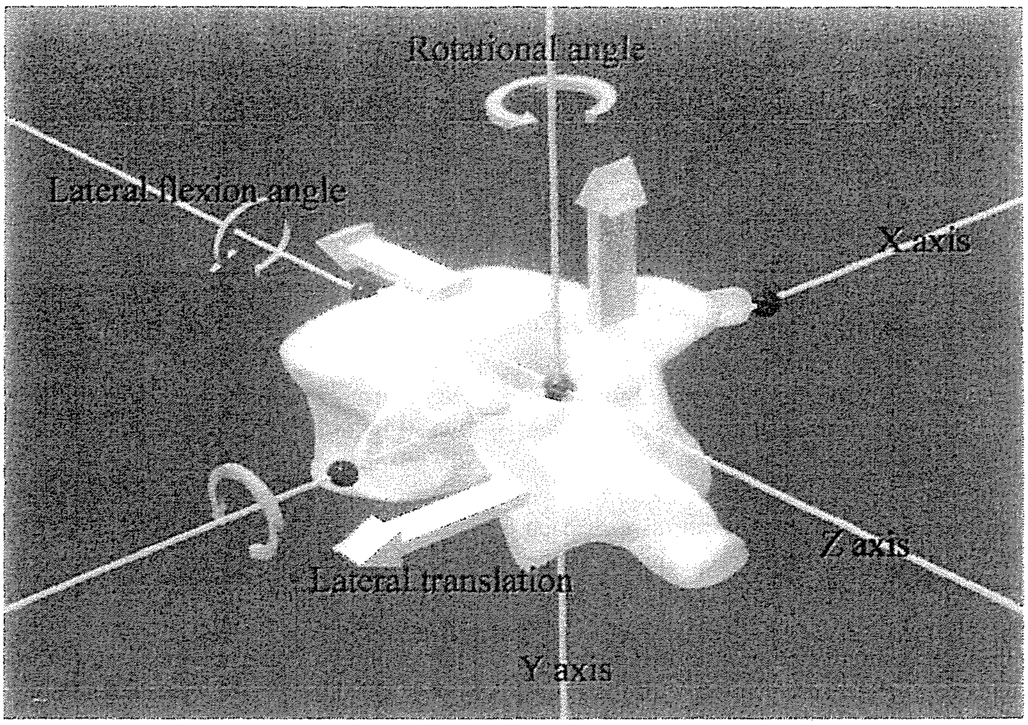


Figure 2 – Three-dimensional positions of the bilateral transverse processes and the upper anterior portion of each vertebral body were calculated from the measured LED positions. The origin of axes of vertebra was defined as the median point of the bilateral transverse processes. The X axis on the horizontal plane was defined as passing through the bilateral transverse processes. The Z axis was defined as the line from the origin to the upper anterior portion of each vertebral body.

contributions of discs and facet joints in preventing lateral translation, the lateral flexion angle and the rotational angle in the removal experiment. A p value of ≤ 0.05 was taken to indicate statistical significance.

Results

In the first experiment, i.e., loading of the 1000-g weight, lateral translation was increased by traction in the LAF direction as compared to that in the LPF direction at L2-3 ($p = 0.025$), L3-4 ($p = 0.022$), and L4-5 ($p = 0.018$) (Figure 3). Lateral translation at L2-3 was significantly greater than that at L5-S ($p = 0.015$) when the specimen was pulled in the LAF direction. The same tendency could be seen when the specimen was pulled in the LPF direction; lateral translation at L2-3 was significantly greater than at L5-S ($p = 0.034$).

Traction in the LAF direction increased the lateral flexion angle more than in the LPF direction at L3-4 ($p = 0.019$). There were no significant differences among L2-3, L4-5, and L5-S regardless of whether the specimen was pulled in the LAF or the LPF direction.

In terms of the rotation angle, traction in the LAF direction was greater than in the LPF direction at L2-3 ($p = 0.022$) and L4-5 ($p = 0.021$). The rotation angle at L2-3 was significantly greater than at L5-S ($p = 0.033$ in LAF, $p = 0.011$ in LPF).

The anterior flexion angle of the intervertebral disc was significantly greater when the specimen was pulled in the LAF direction than when the specimen was pulled in the LPF direction at L2-3 ($p = 0.011$) and L3-4 ($p = 0.041$).

In the removal experiment, lateral translation at all intervertebral spaces increased significantly following resection of discs and facet joints (L2-3, $p = 0.004$; L3-4, $p = 0.001$; L4-5, $p = 0.003$; and L5-S, $p = 0.005$), as shown in Table 1. The lateral flexion angle at all intervertebral spaces increased significantly following resection of discs and facet joints (L2-3, $p < 0.0001$; L3-4, $p = 0.0002$; L4-5, $p < 0.0001$; and L5-S, $p < 0.0001$). The rotation

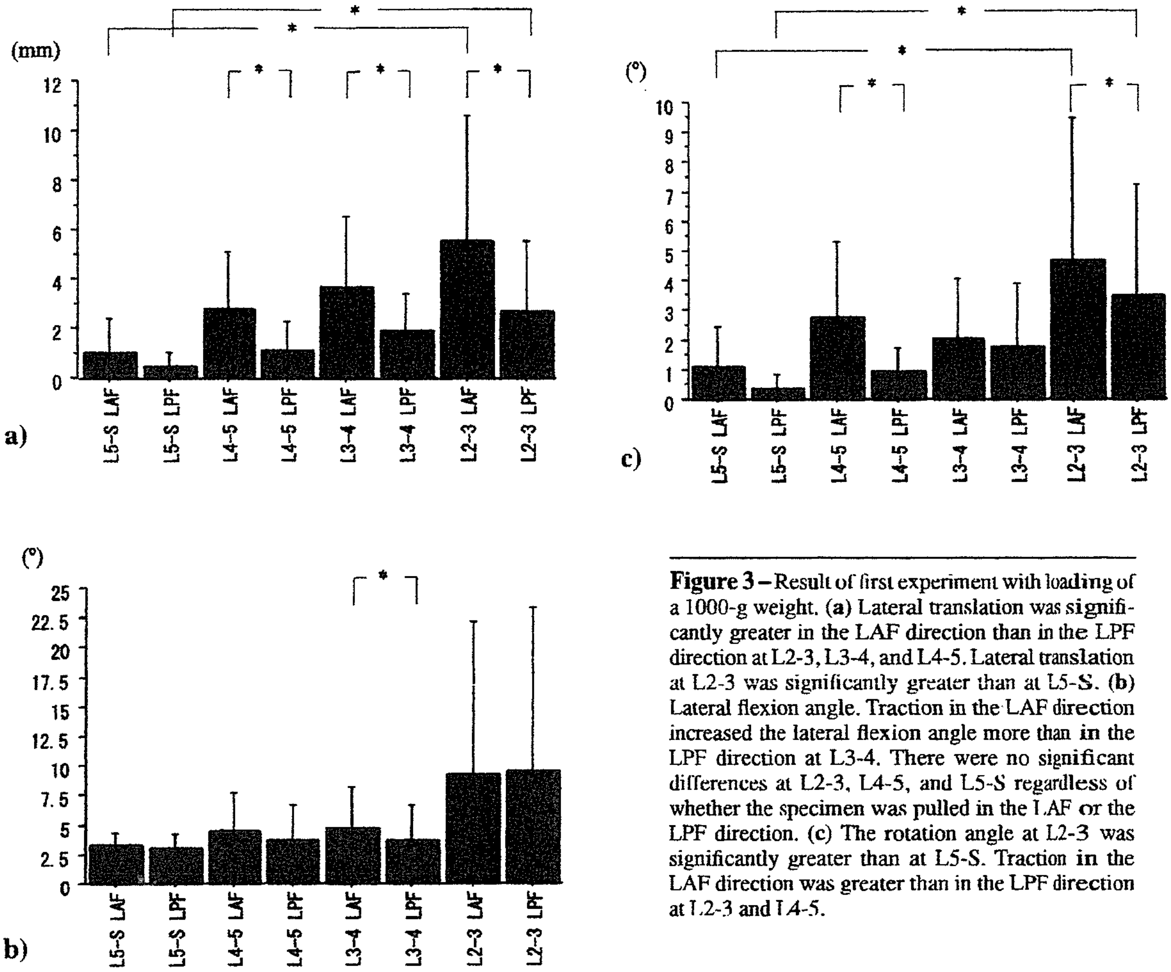


Figure 3 – Result of first experiment with loading of a 1000-g weight. **(a)** Lateral translation was significantly greater in the LAF direction than in the LPF direction at L2-3, L3-4, and L4-5. Lateral translation at L2-3 was significantly greater than at L5-S. **(b)** Lateral flexion angle. Traction in the LAF direction increased the lateral flexion angle more than in the LPF direction at L3-4. There were no significant differences at L2-3, L4-5, and L5-S regardless of whether the specimen was pulled in the LAF or the LPF direction. **(c)** The rotation angle at L2-3 was significantly greater than at L5-S. Traction in the LAF direction was greater than in the LPF direction at L2-3 and L4-5.

Table 1 Result of Removal Experiment

	L5/S	L4/5	L3/4	L2/3
Lateral Translation				
Intact (mm)	1.2 ± 1.6	2.5 ± 2.0	2.6 ± 2.3	3.4 ± 3.5
After discectomy and facetectomy (mm)	4.3 ± 3.0	7.5 ± 4.5	10.3 ± 6.3	9.9 ± 9.2
	$p = 0.005$	$p = 0.003$	$p = 0.001$	$p = 0.004$
Lateral Flexion Angle				
Intact (°)	1.2 ± 0.7	2.3 ± 1.9	2.2 ± 1.9	4.6 ± 1.6
After discectomy and facetectomy (°)	8.6 ± 2.7	12.0 ± 3.3	14.7 ± 5.2	16.5 ± 5.4
	$p < 0.0001$	$p < 0.0001$	$p = 0.0002$	$p < 0.0001$
Rotation Angle				
Intact (°)	1.2 ± 1.0	1.6 ± 1.1	1.4 ± 0.8	3.6 ± 2.0
After discectomy and facetectomy (°)	7.9 ± 4.7	11.0 ± 8.3	10.9 ± 9.2	14.5 ± 7.9
	$p = 0.003$	$p = 0.020$	$p = 0.035$	$p = 0.005$

Note: The lateral translation, lateral flexion angle, and rotation angle increased significantly following resection of discs and facet joints.

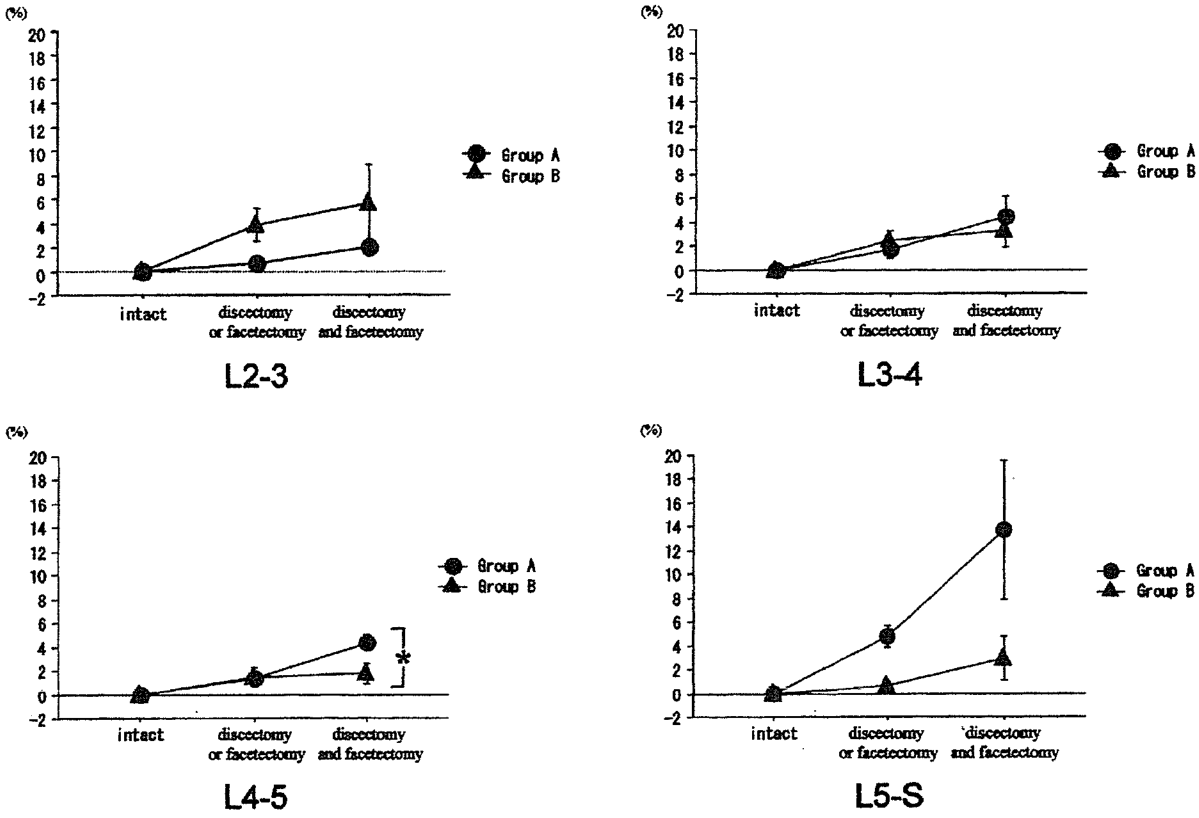


Figure 4 a – Rate of increase with resection compared with the range of motion of the intact specimen. Lateral translation. There was a significant pattern difference at L4-5 between Group A and Group B. At other intervertebral spaces, the pattern of increase with resection in Group A was not significantly different from that in Group B.

angle also increased significantly at all intervertebral spaces (L2-3, $p = 0.005$; L3-4, $p = 0.035$; L4-5, $p = 0.020$; and L5-S, $p = 0.003$).

When the range of motion of the intact specimen was assumed to be 1, the rate of increase in lateral translation with resection [(ROM of each status) / (ROM of intact) −1] showed a significant pattern difference at L4-5 ($p = 0.020$) between Group A and Group B. At other intervertebral spaces, the pattern of increase with resection, in Group A, was not significantly different from that in Group B.

The rate of increase in the lateral flexion angle showed a significant difference in pattern at L2-3 ($p = 0.026$). At other intervertebral spaces, the patterns of increase with resection, in Group A, were not significantly different from those in Group B. As for the rate of increase in the rotational angle, there were no significant differences between Group A and Group B at any of the intervertebral spaces (Figure 4). Throughout all resection steps, lateral translation, lateral flexion and rotation angle at L5-S were smaller than those at other intervertebral spaces.

Discussion

Degenerative lumbar scoliosis is often accompanied by lateral listhesis. Some radiological studies have shown diminution of lordosis to be related to lateral listhesis. Liu, Ray, and Hirsch (1975) attempted to explain the relationship between the loss of lordosis and lateral listhesis.

Some previous biomechanical studies of cadaveric specimens on which pure shear force was loaded demonstrated that the stiffness of the motion segment unit of the lumbar spine ranged from 53 to 643 N mm^{-1} (Liu et al., 1975; Miller, Schultz, Warwick, & Spencer, 1986; Panjabi, Krag, & Chung, 1984). The stiffness of the motion segment was not

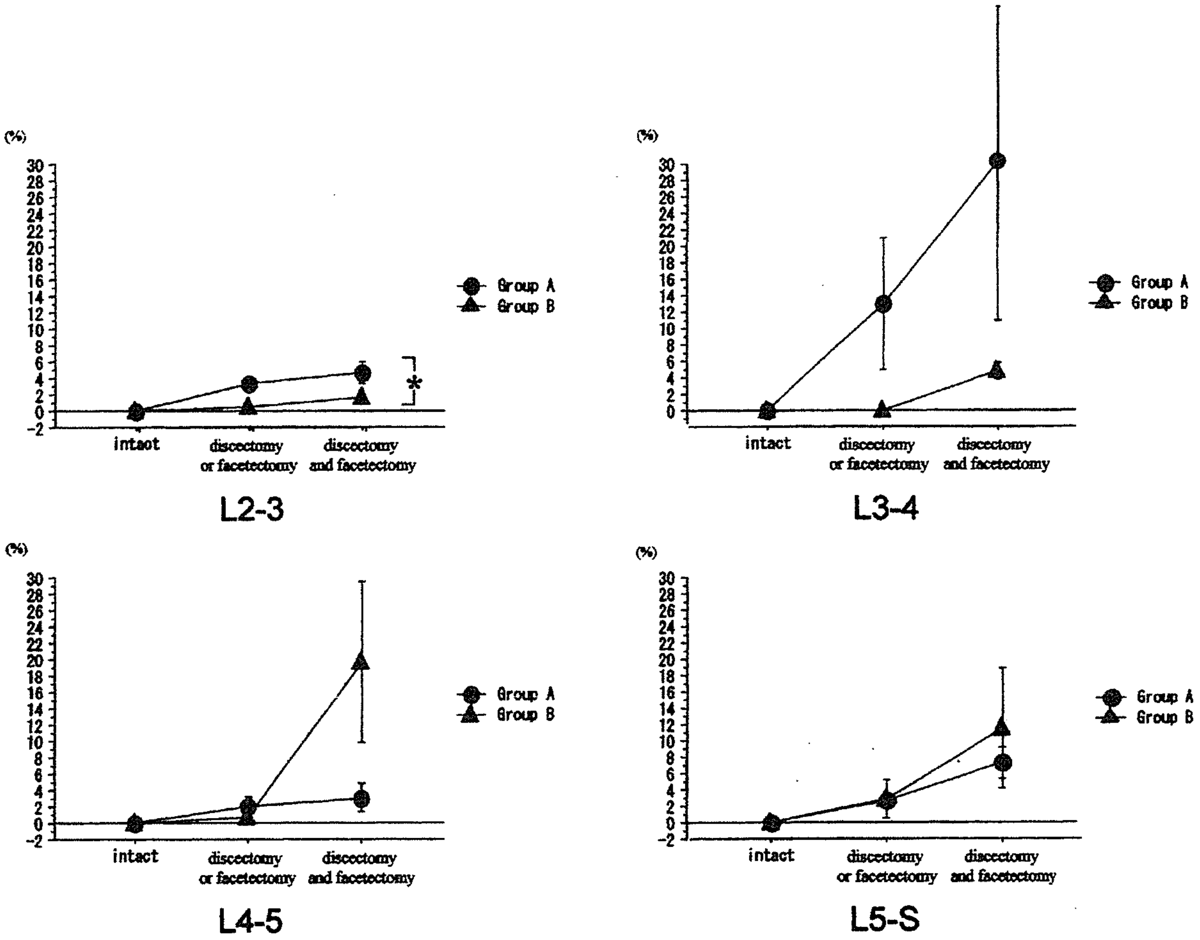


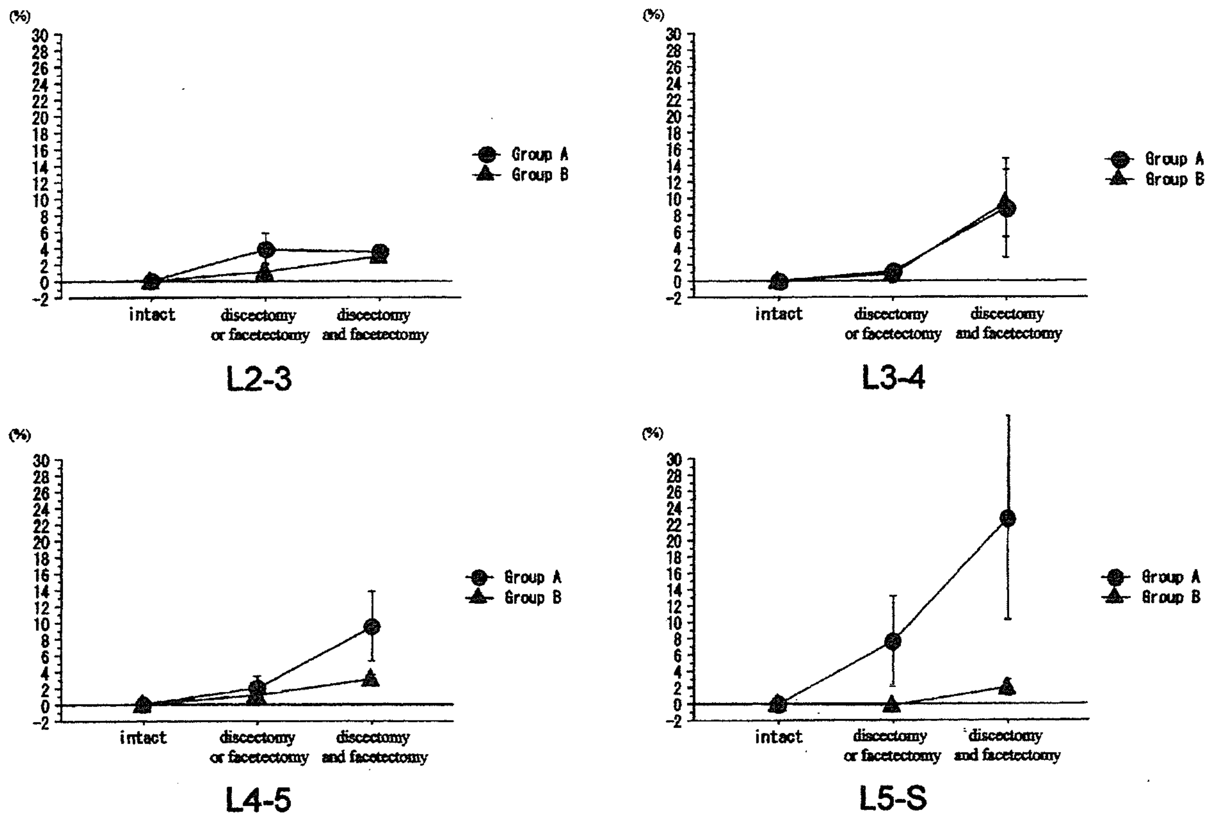
Figure 4 b – Rate of increase with resection compared with the range of motion of the intact specimen. The rate of increase in the lateral flexion angle showed a significant pattern difference at L2-3. At other intervertebral spaces, the patterns of increase with resection in Group A were not significantly different from those in Group B.

determined in the present study because the simulated muscle forces were applied to the specimens instead of pure shear force. However, none of the previous studies focused on the precise relationship between the direction of force and lateral translation, or between facet joints or discs and increased lateral translation.

In our first experiment, traction in the LAF direction increased lateral translation more significantly than in the LPF direction at L2-3, L3-4, and L4-5. Although the actual force and moment loading each vertebra cannot be calculated in this experimental system, it is clear that the anterior flexional moment of the traction in the LAF direction is greater than that of the traction in the LPF direction.

Traction in the LAF direction increased the lateral flexion angle more significantly than in the LPF direction at L3-4. At other intervertebral spaces, there were no significant differences in the lateral flexion angle. The anterior flexion angle of each intervertebral space was significantly greater when the specimen was pulled in the LAF direction than when it was pulled in the LPF direction. A difference was seen in lateral translation according to the tractional direction, LAF or LPF, but not in lateral flexion. This result indicates that force in the anterior direction increases lateral translation more than force in the posterior direction.

The question of which component restrains lateral translation more, facet joints or intervertebral



L2-3

L3-4

L4-5

L5-S

Figure 4 c – Rate of increase with resection compared with the range of motion of the intact specimen. Rotational angle. There were no significant differences between Group A and Group B at any of the intervertebral spaces examined.

discs, remained. Therefore, we performed further removal experiments in order to measure the contributions of discs and facet joints to lateral translation, the lateral flexion angle, and the rotation angle. The removal experiments were carried out using cables because the LAF direction showed larger numerical values than the preceding LPF direction.

In this resection experiment, the pattern of increase in lateral translation differed significantly between Groups A and B at L4-5. The fact that Group B showed a larger rate of increase and that the bilateral facet joints and discs were ultimately removed in both groups indicates that lateral translation increases more when the facet joints are removed than when the discs are removed. Sharma et al. (Sharma, Langrana, & Rodriguez, 1995) reported that the facet joints play an important role in resisting the anterior shear displacement (translation) which accompanies flexion in the sagittal plane. There are no previous detailed studies on the role of the facet joints in resisting lateral translation in the coronal plane. Facet joints are tightened when the lumbar spine is extended posteriorly, preventing the vertebrae from translating laterally, but they are loose when the lumbar spine is bent forward to permit lateral translation between the vertebrae.

Several limitations in our study should be noted. Since the specimens used in this study were obtained from the cadavers of elderly persons, the results may have been affected by degeneration of the discs and the facet joints. However, we think that the results are meaningful because lateral translation of the lumbar spine mostly occurs in the elderly.

In the first experiment, as we designed an apparatus that simulated natural lateral bending motion, it was impossible to calculate the actual force loaded on each vertebra, and the four vector pairs of the cable representing abdominal oblique muscles do not act on each vertebra as pure lateral translational forces. In the second removal experiment, we completely resected facet joints and discs in order to facilitate lateral translation. However, such a situation is unlikely to occur in vivo.

Previous reports have focused on the relationship between discs and lateral translation. Goel et al. (Goel, Goyal, Clark, Nishiyama, & Nye, 1985) reported that lateral translation increased after discectomy in vitro. Recently Krismer et al. (2000) demonstrated with cadaveric specimens that after application of an axial rotation moment, lateral translation increased as the degree of degeneration increased. However, the current study showed lateral translation to be more closely related to facet joints than to discs, because greater translation was seen when the facet joints were removed than when the discs were removed.

The lateral flexion angles were affected more strongly by the removal of discs than by the removal of facet joints at L2-3. Abumi et al. (1990), in an experiment using fresh human lumbar functional spinal units, found that bilateral total facetectomy leads to spinal instability in flexion, but not in lateral bending. The current results are in accordance with those of Abumi et al. in that the range of motion was not affected in lateral bending even after total facetectomy. Mimura et al. (1994) assessed the relationship between spinal instability and disc degeneration. They found the range of motion in lateral bending, which was the sum for the neutral and elastic zones, to decrease with increasing macroscopic and radiographic disc degeneration. The result explained the change in disc height with degeneration. In our experiment, the weight loaded onto the PF cable was attached to the specimen to avoid extreme flexion, which prevented loss of the disc height at the same time. Thus the range of lateral bending increased after discectomy.

There is controversy as to whether rotational torsion of the lumbar spine is resisted by the facet joints or the disc (Adams & Hutton, 1983; Gunzburg, Hutton, & Fraser, 1991). The facet joints prevent extreme rotation by the concave surface of the superior processes and the convex surface of the inferior processes. Gunzburg et al. indicated that the facet joint capsules are more important in resisting rotation in the neutral position than in flexion. In the current study, the rotational angle was very small when the specimen was intact, but the traction in the LAF direction increased the rotational angle more than that in the LPF direction at L3-4 and L4-5, a result which supports the study of Gunzburg et al. In the removal experiments, the rotational angle was affected by the excision of both discs and facet joints. A causal contribution to the rotational angle could not be assumed in the current study.

Some reports have described L5-S1 as being stiffer than other lumbar segments affected by posterior elements: facets, interspinous ligaments, and the ligamentum flavum (McGlashen, Miller, Schultz, & Andersson, 1987; Tsai et al., 2003). The specimens used in the current study were harvested with bilateral preservation of the iliolumbar ligaments. Yamamoto et al. (Yamamoto, Panjabi, Oxland, & Crisco, 1990) used cadaveric specimens to demonstrate that the iliolumbar ligament restricts lateral bending and axial rotation at the L5-S1 joint. In our study, lateral translation and the rotational angle at L5-S were smaller than those of other intervertebral spaces. This result indicates that the iliolumbar ligament restricts not only lateral bending and the rotational angle but also lateral translation.

In conclusion, force in the anterolateral direction increased the lateral translation more than force in the posterolateral direction, and lateral translation was greater when the facet joints were removed than when the discs were removed at the levels of shear loading applied in this study.

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