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·基础研究·

不同预拉伸方式对弹力链力值衰减影响的体外研究

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【摘要】 **目的** 探讨不同预拉伸方式对弹力链力值衰减的影响，为其在临床正畸治疗中的应用提供实验依据。**方法** 选取 5 个圈长度的紧密型弹力链与长距型弹力链样本，分别设置 1 个对照组（未预拉伸）和 15 个实验组（分别按原长度的 25%、50%、100% 进行 1 ~ 5 次循环预拉伸）。所有弹力链样品均以相同初始长度固定于测试装置。为模拟牙齿移动，每周调整固定装置使链长缩短 0.35mm。在 4 周实验周期内，分别于即刻、4 h、8 h、24 h、7 d、14 d、21 d、28 d 时间点测量各组剩余力值，同时实验全程在模拟唾液环境结合温度循环条件下进行。**结果** 预拉伸长度与次数对弹力链剩余力值的影响存在显著交互作用（$P<0.001$）。在紧密型弹力链中，25%（$P=0.001$）及 50%（$P=0.005$）原长预拉伸 3 次组在 24 h 的剩余力值高于对照组，差异具有统计学意义；在 7、14、21、28 d 时间点，25%、50% 和 100% 原长度预拉伸 3 次组的剩余力值高于对照组，差异具有统计学意义（$P<0.001$）。当固定预拉伸 3 次时，50% 原长预拉伸 3 次组与 25%（$P=0.617$）、100%（$P=0.229$）原长预拉伸 3 次组在 7 d 时剩余力值差异无统计学意义，但在 14 d 时显著高于 25%（$P=0.003$）及 100%（$P=0.027$）原长预拉伸 3 次组，差异具有统计学意义；21 d 时，50% 原长预拉伸 3 次组剩余力值高于 100% 原长预拉伸 3 次组，差异具有统计学意义（$P=0.020$），但与 25% 原长预拉伸 3 次组差异无统计学意义（$P=0.052$）；至 28 d 时，50% 原长预拉伸 3 次组剩余力值高于 25%（$P=0.003$）、100%（$P=0.003$）原长预拉伸 3 次组，差异具有统计学意义。在长距型弹力链中，50% 原长预拉伸 3 次组在 8 h（$P=0.005$）与 24 h（$P<0.001$）的剩余力值高于对照组，差异具有统计学意义。在 7、14、21、28 d 时间点，25%（7、14 d：$P<0.001$；21 d：$P=0.003$；28d：$P=0.008$）、50%（$P<0.001$）及 100%（$P<0.001$）原长预拉伸 3 次组的剩余力值均高于对照组，差异具有统计学意义。当固定预拉伸 3 次时，50% 原长预拉伸 3 次组在 7、14、21、28 d 的剩余力值均高于 25% 原长预拉伸 3 次组（$P<0.001$），差异具有统计学意义；虽然 50% 原长预拉伸 3 次组在 14 d（$P=0.068$）剩余力值与 100% 原长预拉伸 3 次组差异无统计学意义，但在 7 d（$P<0.001$）、21 d（$P=0.005$）、28 d（$P<0.001$）时均高于 100% 原长预拉伸 3 次组，差异具有统计学意义。**结论** 适当的预拉伸方式能有效延缓其力值衰减；预拉伸 50% 原长度 3 次的预拉伸方式可最大程度缓解弹力链的力值衰减。

【关键词】 正畸治疗； 弹力链； 初始力值； 力值衰减； 预拉伸； 剩余力值； 牙齿移动； 口腔环境

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Effect of different pre-stretching methods on the force degradation of elastomeric chains: an *in vitro* study

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【Abstract】 **Objective** To investigate the effect of different pre-stretching on the force degradation of elastomeric chains methods and provide experimental evidence for its application in clinical orthodontic treatment. **Methods** One control group (no pre-stretched treatment) and 15 experimental groups (pre-stretched to 25%, 50%, and 100% of the original length in 1 - 5 cycles) were set up by taking five loop lengths of short elastomeric chain and long elastomeric chain samples, respectively. The elastomeric chains from both the control and experimental groups were mounted on the testing fixture at identical initial lengths. To simulate tooth movement, the fixation device was adjusted to reduce the distance by 0.35 mm weekly. The remaining force of each group was measured at different time points over a 4-week period. Further, the experiment was conducted in a simulated salivary environment with additional thermal cycling. **Results** Pre-stretching length and cycles showed a significant interaction effect on the remaining force of elastomeric chains (P < 0.001). For short elastomeric chains, the groups pre-stretched to 25% (P = 0.001) and 50% (P = 0.005) of the original length for 3 cycles showed significantly higher remaining force values than the control group at 24 h. At 7, 14, 21, and 28 d, the groups pre-stretched to 25%, 50%, and 100% of the original length for 3 cycles consistently maintained higher remaining force values than the control group (P < 0.001). Within the groups of 3 pre-stretching cycles, no significant differences in remaining force were observed among the 50% group and the 25% (P = 0.617) or 100% (P = 0.229) groups at 7 d. However, at 14 d, the remaining force of the 50% group was significantly higher than that of both the 25% (P = 0.003) and 100% (P = 0.027) groups. At 21 d, the 50% group maintained a significantly higher remaining force compared to the 100% group (P = 0.020), but the difference compared to the 25% group did not reach statistical significance (P = 0.052). By 28 d, the remaining force of the 50% group remained significantly higher than that of both the 25% (P = 0.003) and 100% (P = 0.003) groups. For long elastomeric chains, the 50% pre-stretch (3 cycles) group showed significantly higher remaining force values than the control group at 8 h (P = 0.005) and 24 h (P < 0.001). Throughout the experimental period at 7, 14, 21, and 28 d, the remaining force values of the 25% (7, 14 d: P < 0.001; 21 d: P = 0.003; 28 d: P = 0.008), 50% (P < 0.001), and 100% (P < 0.001) original length pre-stretching for 3 cycles groups were consistently higher than those of the control group. Within the groups of 3 pre-stretching cycles, the remaining force of the 50% original length pre-stretching for 3 cycles group was significantly higher than that of the 25% original length pre-stretching for 3 cycles group at all of the time points from 7 to 28 d (P < 0.001). Although no statistically significant differences were observed between the 50% and 100% groups at 14 d (P = 0.068), the 50% group exhibited significantly higher remaining force than the 100% group at 7 d (P < 0.001), 21 days (P = 0.005), and 28 days (P < 0.001). **Conclusion** Appropriate pre-stretching methods can effectively delay the force degradation of the elastomeric chain. Pre-stretching to 50% original length for three cycles can maximize the delay of the force degradation of the elastomeric chain.

【Key words】 orthodontic treatment;　elastomeric chain;　initial force;　force degradation;　pre-stretch;　remaining force;　tooth movement;　oral environment

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弹力链广泛应用在正畸治疗中持续施加矫治力以促进牙齿移动[1]，特别是在前牙内收、间隙关闭、牙齿旋转等方面展现出显著疗效[2-4]。然而，弹力链主要成分为聚氨酯，其力学机制源于作为高分子弹性材料所固有的“粘弹性”行为，具体表现为“应力松弛”现象[5]。当弹力链被拉伸至固定长度（恒定应变）并保持时，其内部的高分子链会发生随时间推移的分子链滑移、取向重构等变化[6]，这一微观层面的结构变化过程，在宏观上直接体现为材料内部应力的持续下降，即输出力值的衰减[7-8]。研究显示，这种衰减在初始24 h内尤为明显，力值可损失50% ~ 75%[9]，为了弥补这一损失，第1天可能需要施加4倍预期的力作用于牙齿[10]，但这可能引起牙根吸收、支抗丢失等不良反应[11-12]，同时过大的初始正畸力可能造成患者的疼痛不适[13]。因此，为了在体外预先完成或削弱这

一不利的初始应力松弛过程，有学者提出在体外对其进行预拉伸处理，使其初始力值衰减在临床使用前完成[14-15]。在材料学机制上，未经预拉伸的弹力链在初始使用阶段表现出显著的循环软化，而预拉伸则通过预先消耗"可软化"组分来稳定其力学性能[16]。相关研究设置了不同的预拉伸时间探究预拉伸对弹力链剩余力值的影响[17-18]，而在实验过程中弹力链预拉伸后拉伸至相同力值所产生的不同应变量对弹力链力学性能也存在影响[19]。de Aguiar等[20]则通过设置单一预拉伸方式与对照组进行比较，进一步验证了预拉伸的处理效果。然而，上述研究均未将临床正畸治疗中牙齿持续移动对弹力链力值衰减的动态影响纳入实验设计。另一项由Jung等[21]开展的研究在生理盐水环境中将弹力链预拉伸至100%，并设置了1～5次循环预拉伸，通过负载-位移曲线探究了在模拟1 mm牙齿移动距离时，不同预拉伸次数对其力学性能的影响，但该研究未对预拉伸后力值随时间变化的实际衰减过程进行定量监测。此外，在实际弹力链力值随时间衰减的过程中，口腔环境、温度、唾液酶等因素会增加弹力链的永久变形，从而影响其力值变化[22-24]。

在正畸治疗中，牙齿受力移动导致弹力链拉伸长度减少，预拉伸能否影响弹力链力值的衰减，以及弹力链采用不同的预拉伸方式后力值随时间的变化是否有显著差异，值得进一步研究。在实验设计中，模拟口腔真实环境是准确评估弹力链力值衰减的关键，本研究模拟了口腔内冷热交替的唾液环境，分析比较不同预拉伸长度及次数组合的多种预拉伸方式对弹力链剩余力值的影响。此外，本研究设置了每周递减弹力链拉伸长度的装置，以此模拟实际加力周期中牙齿移动的过程。

1 材料和方法

1.1 设备和材料

万能材料力学实验机器（Instron公司，美国）；电热恒温水浴箱（HH·W420，常州苏瑞，中国）；电子数显游标卡尺（分辨率0.01 mm，杭州德西力，中国）；3M Unitek Orthodontic Products弹力链（紧密型批号404—256，长距型批号406—612，3M，美国）；人工唾液（NaCl，KCl，$CaCl_4$ · $2H_2O$，NaH_2PO_4 · $2H_2O$，Na_2S·$2H_2O$，Urea，淀粉酶，纯净水，用HCl和NaOH滴定调整pH值至6.8，东莞创峰，中国）；成品不锈钢弯钩及自凝树脂磨具自制弹力链预拉伸装置；不锈钢条、1 mm直径不锈钢柱及螺丝螺母自制弹力链距离固定装置。

1.2 实验分组及方法

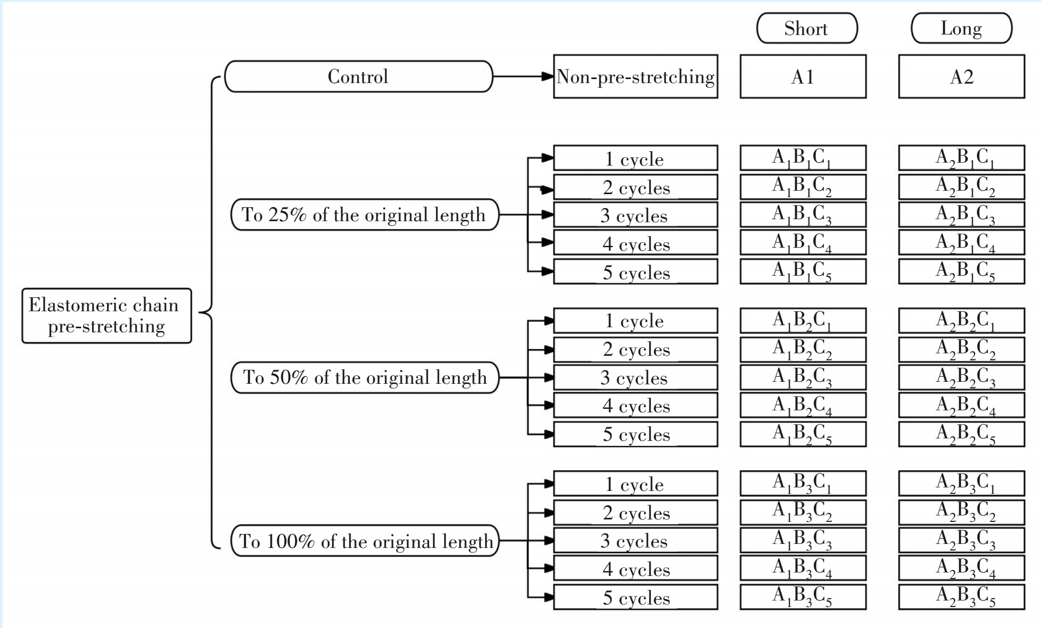
本研究共制备768个弹力链实验样本，对照组为48个（设置2种弹力链×8个时间点，n = 3）和实验组为720个（设置2种弹力链×3种预拉伸长度×5预拉伸次数×8个时间点，n = 3）。实验组参数设置及实验分组情况分别见表1、图1。

表1 实验所设置的影响因子
Table 1 Impact factor of the study

Elastomeric chain form(A)	Pre-stretching length(B)	Pre-stretching cycles (C)
1 (Short) 2 (Long)	1 (Pre-stretching 25%) 2 (Pre-stretching 50%) 3 (Pre-stretching 100%)	1 (One cycle) 2 (Two cycles) 3 (Three cycles) 4 (Four cycles) 5 (Five cycles)

测量5个圈长度紧密型及长距型弹力链样品初始长度L1、L2，制作弹力链测力工具（图2a），分别测得其拉伸至150 g力值负荷时的位移量D1、D2（图2b）；制作弹力链预拉伸装置（图2c），预拉伸速度统一设置为50 mm/min速度，以排除预拉伸速度不一致对实验结果的影响，紧密型弹力链预拉伸组合分别各拉伸24段（图2d）。长距型弹力链重复以上操作。

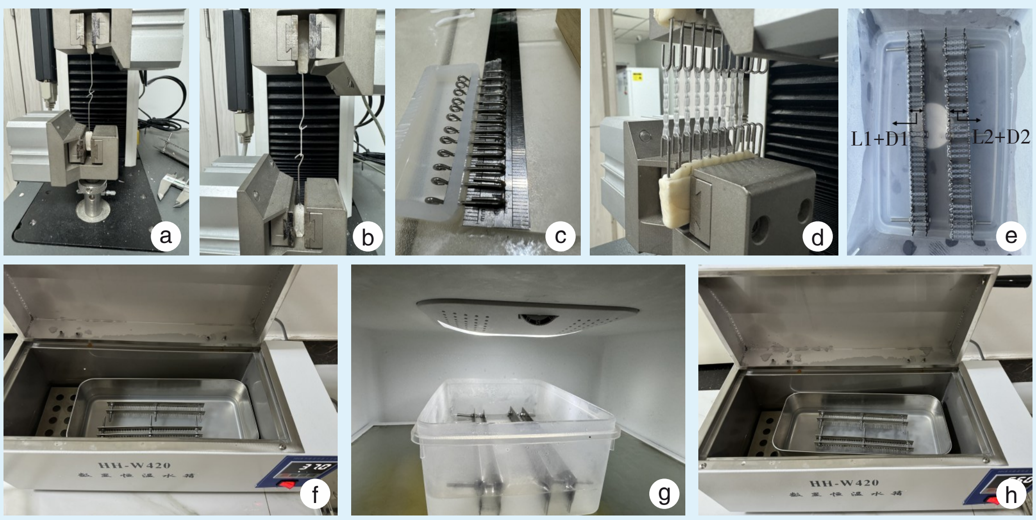
将两种弹力链预拉伸处理后分别按L1+D1、L2+D2距离固定于保持固定至可调节距离的固定装置（图2e）放于37 ℃人工唾液中恒温水浴（图2f），并设置每天冷热循环模拟：将保持装置浸泡预先放置于5 ℃低温冰箱内的人工唾液中（图2g），持续浸泡30 s，随后将保持装置迅速转移至另一含有55 ℃人工唾液的恒温水浴箱中，同样浸泡30 s（图2h）。每次温度冷热模拟完成30次完整循环，每日进行两次温度冷热模拟。循环结束后，将实验装置放在37 ℃恒温水浴箱人工唾液中。在预拉伸后即刻测量各组剩余力值以及当弹力链浸泡4 h、8 h、24 h、7 d、14 d、21 d及28 d时，分别测量各组各时间点剩余力。每周调节固定装置两端距离缩小0.35 mm以模拟牙齿移动。紧密型弹力链及长距型弹力链在即刻、4 h、8 h、24 h测力时间点拉伸长度分别取位移距离D1、D2，此后每周测量拉伸长度为上一周测量拉伸长度减去0.35 mm（图3），每组每次测力重复3次取平均值。所有弹力链样本的剩余力值测定均由同一名实验员完成，以规避人为测量偏倚。



Impact factors (A, B, C) of the study showed in Table 1

Figure 1　Schematic diagram of experimental grouping situation

图 1　实验分组情况示意图



a: the force measuring hook; b: the force measurement of samples; c: the manufacture of the elastomeric chain pre-tensioning device; d: the pre-stretching process of the samples; e: the short elastomeric chain is fixed at the distance L1 + D1 on the device, and the long elastomeric chain is fixed at the distance L2 + D2; f: the samples were dropped into an artificial saliva environment at 37 °C in electrothermal constant temperature water; g: the samples were immersed in artificial saliva environment that has been pre-placed in a low-temperature refrigerator at 5 °C; h: the samples were immersed in artificial saliva environment at 55 °C in electrothermal constant temperature water

Figure 2　Pre-stretching treatment and measurement of remaining force

图 2　预拉伸处理及力值测定

1.3　统计学分析

在本研究中，所收集的数据通过 IBM SPSS Statistics 27（IBM 公司，美国）进行统计分析，首先采用线性混合模型分析将时间点、预拉伸长度、预拉伸次数作为固定因子，用于评估各因素的主效应及交互效应对剩余力值的整体影响。为验证线性混合模型结果的稳健性，并呈现整体组间比较的直观结果，进一步采用重复测量方差分析（Repeated Measures ANOVA）以时间为组内因子，预拉伸长度与预拉伸次数的组合（共 16 组，含 1 个对照组和 15 个实验组）为组间因子，基于边际均值进行 Bonferroni 多重比较。包含 8 个时间点的边际均值两两成

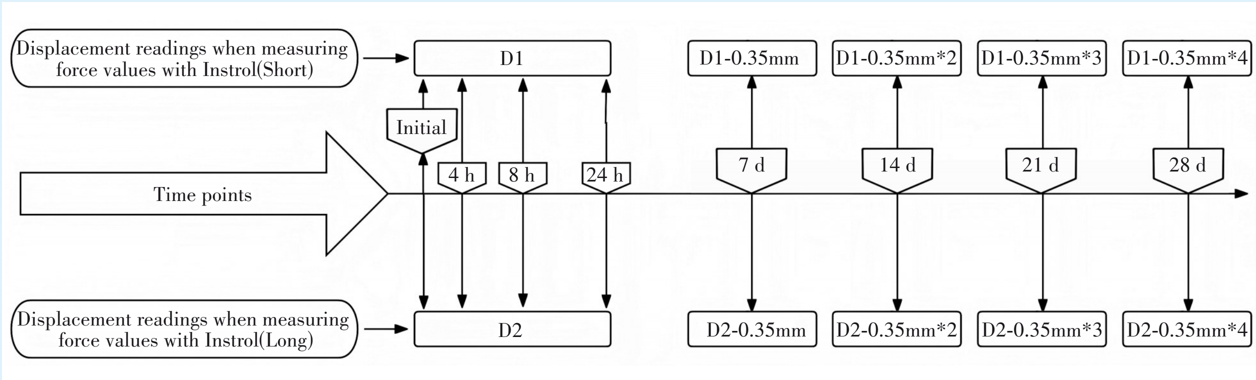


Figure 3 Time points of force measurement and displacement each time point

图3 弹力链测力时间点及测力读数时位移

对比较以及各组之间整体剩余力值进行多重比较，探究预拉伸后弹力链整体剩余力值随时间变化的同时，比较不同预拉伸方法的整体组间差异。此外，若时间与组别的交互效应显著，则在各时间点进一步进行组间方差分析及Bonferroni多重比较校正，以增加结论可靠性。所有检验以$P<0.05$为有统计学意义。

2 结 果

2.1 不同时间点各组剩余力值及固定效应检验

两种弹力链所测剩余力值见表2 &表3。采用线性混合模型固定效应检验，结果显示，力值随时间发生变化，差异具有统计学意义($P<0.001$)。预拉伸长度与预拉伸次数存在显著交互作用，差异具有统计学意义($P<0.001$)，即不同预拉伸长度条件下，预拉伸次数对弹力链力值变化的影响存在差异，二者并非独立影响弹力链剩余力值。此外，预拉伸长度与预拉伸次数的组合效应随测量时间点的不同而变化，差异均具有统计学意义(紧密型$P<0.001$，长距型$P=0.012$)(表4)。以上结果表明，不同预拉伸方式的影响在不同时间点发生动态改变，需通过不同时间点进行两两比较。

2.2 紧密型弹力链各组间剩余力值对比分析

紧密型弹力链各组的力值变化曲线见图4，可以观察到所有预拉伸处理均降低了初始力值。在不同时间点进一步对比发现，25%($P=0.001$)及50%($P=0.005$)原长预拉伸3次组在24 h的剩余力值已高于对照组，差异具有统计学意义。在复诊周期中后期的关键时间点(7、14、21、28 d)，25%、50%和100%原长度预拉伸3次组的剩余力值仍高于对照组，差异具有统计学意义($P<0.001$)。而当固定预拉伸3次时，50%组与25%原长预拉伸3次组($P=0.617$)、100%($P=0.229$)原长预拉伸3次组在7 d时剩余力值差异无统计学意义，但在14 d时剩余力值高于25%原长预拉伸3次组($P=0.003$)及100%原长预拉伸3次组($P=0.027$)，差异有统计学意义；21 d时，50%原长预拉伸3次组剩余力值高于100%原长预拉伸组($P=0.020$)，但与25%原长预拉伸3次组比较，差异无统计学意义($P=0.052$)；至28 d时，50%原长预拉伸3次组剩余力值仍然高于25%原长预拉伸3次组($P=0.003$)和100%原长预拉伸3次组($P=0.003$)，差异具有统计学意义。通过各组间整体剩余力值比较及不同时间点各组间剩余力值分层比较，表明紧密性弹力链预拉伸50%原长度3次相对其他预拉伸方式在延缓弹力链力值衰减上取得较为显著的效果。

2.3 长距型弹力链各组间剩余力值对比分析

长距型弹力链各组力值变化曲线(图5)呈现与紧密型弹力链相似的趋势，所有预拉伸处理均明显降低了初始力值。其中，50%原长预拉伸3次组在8 h($P=0.005$)与24 h($P<0.001$)的剩余力值高于对照组。在7、14、21、28 d时间点，25%(7、14 d，$P<0.001$；21 d，$P=0.003$；28d，$P=0.008$)、50%($P<0.001$)及100%($P<0.001$)原长预拉伸3次组的剩余力值均高于对照组。在固定预拉伸次数为3次的组间比较中，50%原长预拉伸3次组在7~28 d的剩余力值均高于25%原长预拉伸3次组，差异具有统计学意义($P<0.001$)；虽然50%原长预拉伸3次组在14 d($P=0.068$)剩余力值与100%原长预拉伸3次组差异无统计学意义，但在7 d($P<0.001$)、21 d($P=0.005$)、28 d($P<0.001$)时均显著高于100%原长预拉伸3次组。以上结果说明，对于长距型弹力

表2　紧密型弹力链不同实验组在不同时间点剩余力值

Table 2　Remaining force of the short elastomeric chains in each group at different time points　g, $\bar{x}$±s

Groups	Initial	4 h	8 h	24 h	7 d	14 d	21 d	28 d
Control	150.00	132.80±5.28	130.93±4.82	115.23±3.01	79.53±3.68	66.67±1.96	45.50±1.57	23.07±1.56
$A_1B_1C_1$	138.80±3.68	121.67±1.48	118.03±7.47	119.33±3.86	85.17±3.70	76.67±2.79[a]	50.23±7.15	25.27±4.50
$A_1B_1C_2$	139.27±6.1	131.13±4.38	136.77±1.84	119.70±3.72	96.73±2.14[a]	86.17±0.25[a]	55.60±4.39[a]	34.73±4.05[a]
$A_1B_1C_3$	128.07±9.71[a]	128.30±1.9	136.63±4.51	126.30±4.68[a]	105.67±1.86[a]	89.73±2.21[a]	63.53±5.72[a]	38.30±1.05[a]
$A_1B_1C_4$	138.53±8.98	126.57±1.55	127.83±1.60	118.13±6.69	101.17±2.81[a]	85.37±2.84[a]	59.83±2.30[a]	30.70±2.04[a]
$A_1B_1C_5$	144.73±2.72	123.27±0.91	124.3±7.67	124.70±4.33[a]	94.87±1.53[a]	82.47±3.07[a]	57.90±4.40[a]	28.60±0.53[a]
$A_1B_2C_1$	131.27±4.36[a]	126.87±0.74	121.73±3.49	114.30±1.56	79.20±4.78	80.57±6.67[a]	56.07±6.13[a]	31.57±0.96[a]
$A_1B_2C_2$	120.80±12.42[a]	122.37±1.77	123.77±1.82	115.23±1.01	82.03±4.51	75.50±2.15[a]	59.53±2.40[a]	24.90±0.46
$A_1B_2C_3$	107.07±4.41[a]	137.00±2.05	137.87±9.96	124.67±2.68[a]	107.37±2.15[a]	98.87±4.14[a]	72.37±1.36[a]	43.83±2.48[a]
$A_1B_2C_4$	112.27±13.12[a]	108.53±5.13[a]	127.30±2.13	116.03±1.70	89.77±3.16[a]	76.93±4.38[a]	56.23±4.78[a]	25.83±3.65
$A_1B_2C_5$	92.53±10.36[a]	121.33±7.24	131.70±3.84	122.20±5.90[a]	100.23±1.45[a]	82.33±3.42[a]	57.67±1.40[a]	21.67±2.72
$A_1B_3C_1$	103.83±6.07[a]	113.10±3.3[a]	110.23±10.07[a]	114.90±1.51	93.57±7.32[a]	76.23±2.69[a]	58.83±4.39[a]	34.93±2.35[a]
$A_1B_3C_2$	105.43±6.13[a]	114.60±1.31[a]	115.03±7.60	115.07±3.67	101.37±0.76[a]	80.80±1.80[a]	59.03±1.64[a]	32.33±5.31[a]
$A_1B_3C_3$	108.23±0.40[a]	121.73±1.70	122.87±4.91	119.70±2.52	103.10±6.53[a]	92.93±1.72[a]	65.37±3.72[a]	38.33±0.78[a]
$A_1B_3C_4$	100.93±3.19[a]	109.13±6.85[a]	116.10±4.12	107.13±4.79[a]	96.07±9.42[a]	79.03±4.58[a]	58.77±1.19[a]	34.57±3.01[a]
$A_1B_3C_5$	105.90±3.73[a]	106.10±3.60[a]	111.53±4.35[a]	113.73±3.63	83.73±3.83	64.80±1.30	46.30±2.10	28.73±3.30[a]

Data are expressed as mean ± standard deviation (n = 3, with three independent samples per group; each sample was measured three times and the average value was used for analysis). Intergroup comparisons were performed using repeated measures analysis of variance (ANOVA), with multiple comparisons adjusted by the Bonferroni correction. At each time point, superscript "a" denotes a statistically significant difference compared with the control group (P < 0.05). The control group did not adopt any pre-stretching. The parameter settings and experimental grouping of the experimental group are shown in Table 1 and Figure 1, respectively

表3　长距型弹力链不同实验组在不同时间点剩余力值

Table 3　Remaining force of the long elastomeric chains in each group at different time points　g, $\bar{x}$±s

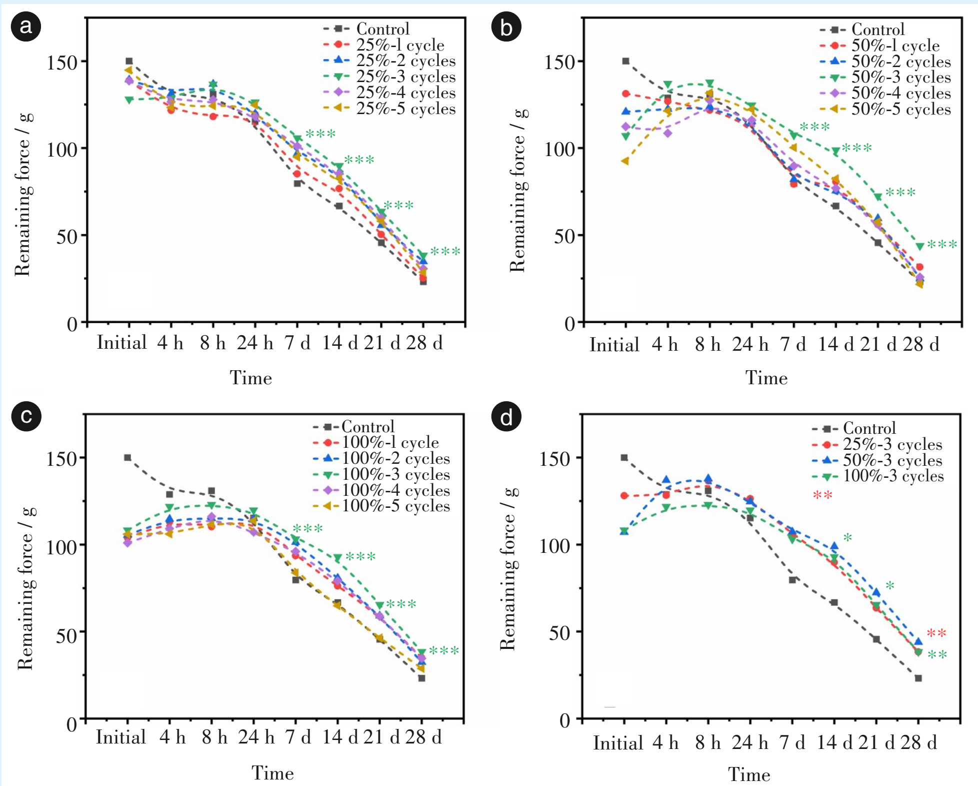
Groups	Initial	4 h	8 h	24 h	7 d	14 d	21 d	28 d
Control	150.00	116.00±7.51	109.30±9.04	98.63±3.71	64.13±3.12	55.60±2.76	46.90±2.34	35.13±1.76
$A_2B_1C_1$	119.30±3.70[a]	115.37±11.27	107.17±3.39	99.60±5.47	64.00±3.73	54.27±4.00	36.47±2.33[a]	28.13±3.27[a]
$A_2B_1C_2$	117.57±4.63[a]	117.43±1.31	110.37±4.59	105.90±2.17	61.83±5.33	64.67±1.59[a]	38.60±1.50[a]	33.03±4.92
$A_2B_1C_3$	108.10±6.47[a]	117.37±4.47	116.23±2.74	110.07±7.07[a]	74.87±2.43[a]	68.80±1.23[a]	53.43±3.07[a]	43.90±3.41[a]
$A_2B_1C_4$	108.53±13.95[a]	113.57±0.71	108.5±11.54	102.83±1.86	69.83±2.39[a]	63.73±4.17[a]	49.33±2.16	35.97±2.90
$A_2B_1C_5$	100.13±21.98[a]	115.27±2.59	109.47±7.32	105.50±4.68	68.97±2.03	59.83±1.97	48.57±1.88	30.80±3.44
$A_2B_2C_1$	124.03±4.31[a]	112.47±5.43	103.87±6.23[a]	101.2±10.58	77.67±1.75[a]	74.57±3.19[a]	56.60±4.19[a]	47.23±4.32[a]
$A_2B_2C_2$	122.53±3.78[a]	115.50±4.52	125.9±4.01	103.9±2.91	68.70±0.95	60.73±2.23[a]	56.23±1.99[a]	41.47±6.95[a]
$A_2B_2C_3$	108.53±2.73[a]	123.87±2.19	129.30±7.63	121.57±4.31[a]	95.27±1.23[a]	77.77±1.29[a]	68.27±1.76[a]	59.73±5.64[a]
$A_2B_2C_4$	103.47±2.47[a]	108.93±10.52	107.27±8.4	96.00±9.74	74.63±3.96[a]	68.93±2.74[a]	52.47±2.99[a]	34.13±1.32
$A_2B_2C_5$	110.20±11.92[a]	117.60±9.06	110.80±10.53	108.80±8.52[a]	71.00±3.08[a]	64.30±3.92[a]	49.53±2.07	31.43±2.48
$A_2B_3C_1$	95.43±5.43[a]	103.00±3.98[a]	90.57±4.29[a]	94.30±1.77	73.10±5.05[a]	66.90±4.69[a]	52.57±1.16[a]	43.80±1.87[a]
$A_2B_3C_2$	90.07±0.25[a]	101.30±3.30[a]	91.37±6.21[a]	95.37±4.25	64.87±3.53	63.30±0.87[a]	49.67±2.30	30.57±4.56
$A_2B_3C_3$	61.67±4.06[a]	102.13±1.51[a]	102.67±10.55	100.30±4.16	77.87±5.66[a]	74.57±1.75[a]	58.67±4.38[a]	50.53±2.31[a]
$A_2B_3C_4$	68.83±8.97[a]	101.43±2.06[a]	89.73±3.25	85.57±2.07[a]	69.93±2.71[a]	68.83±3.48[a]	52.80±1.47[a]	37.70±1.47
$A_2B_3C_5$	68.00±4.61[a]	101.87±2.50[a]	91.90±10.14[a]	87.83±2.81[a]	62.40±2.79	51.90±1.40	44.93±1.72	26.77±4.37[a]

Data are expressed as mean ± standard deviation (n = 3, with three independent samples per group; each sample was measured three times and the average value was used for analysis). Intergroup comparisons were performed using repeated measures analysis of variance (ANOVA), with multiple comparisons adjusted by the Bonferroni correction. At each time point, superscript "a" denotes a statistically significant difference compared with the control group (P < 0.05). The control group did not adopt any pre-stretching. The parameter settings and experimental grouping of the experimental group are shown in Table 1 and Figure 1, respectively

表 4　线性混合模型分析固定效应检验

Table 4　Fixed effects tests from linear mixed model analysis

	Short		Long	
	F	P	F	P
Pre-stretching lengths	110.827	<0.001	148.994	<0.001
Pre-stretching cycles	64.379	<0.001	35.839	<0.001
Times	3125.832	<0.001	1213.322	<0.001
Pre-stretching lengths * Pre-stretching cycles	10.665	<0.001	7.140	<0.001
Pre-stretching lengths * Pre-stretching cycles * Times	5.645	<0.001	1.566	0.012



Data are expressed as mean ± standard deviation (n = 3, with three independent samples per group; each sample was measured three times and the average value was used for analysis). Intergroup comparisons were performed using repeated measures analysis of variance (ANOVA), with multiple comparisons adjusted by the Bonferroni correction. Compare with the control group, *P < 0.05, **P < 0.01, ***P < 0.001. In figure a-c, compared with the control group at the same time point; in figure d, compared with the 50% original length pre-stretching for 3 cycles group. The control group did not adopt any pre-stretching, and the parameter settings and experimental grouping of the experimental group are shown in Table 1 and Figure 1, respectively the control group did not adopt any pre-stretching, and the parameter settings and experimental grouping of the experimental group are shown in Table 1 and Figure 1, respectively

Figure 4　Curves of force degradation on each group of short elastomeric chains

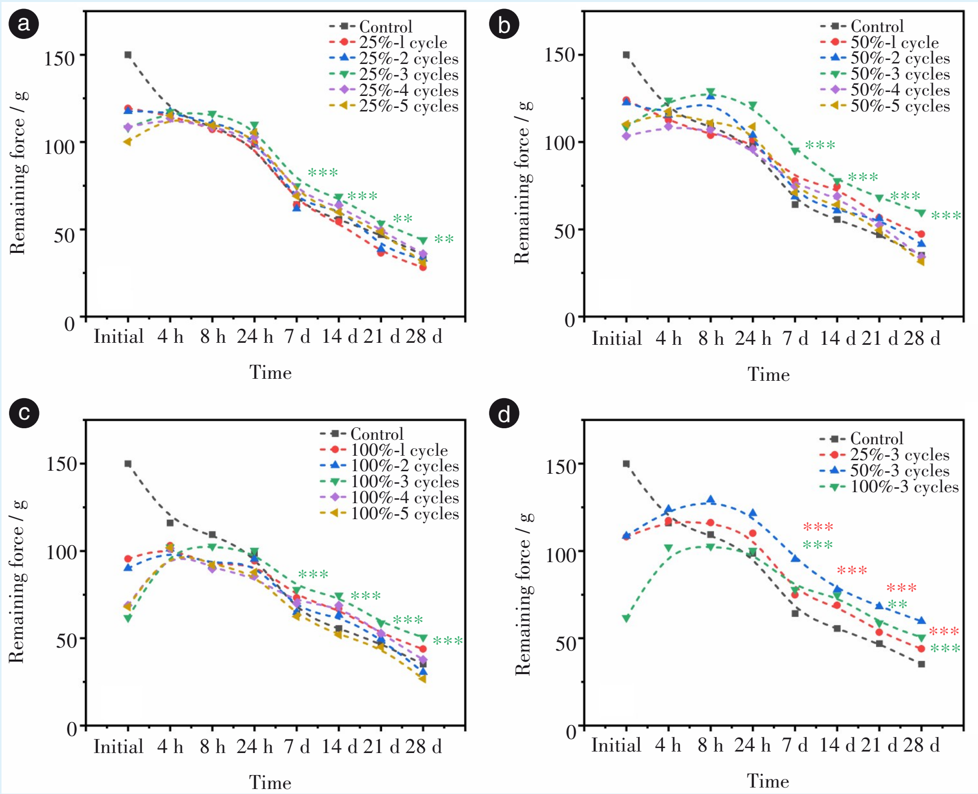
图 4　紧密型弹力链各组剩余力值变化曲线

链，采用 50% 原长度进行 3 次预拉伸，同样是延缓其力值衰减最有效的预拉伸方式。

3 讨　论

3.1　预拉伸对弹力链剩余力值的影响

未经预拉伸处理的弹力链在口内使用时经历首次形变后发生不可逆的微观结构变化，表现为力值降低。这种现象在橡胶力学中称为 Mullins 效应[25]。预拉伸的本质，就是在体外可控条件下，完成此次首次形变过程，从而主动诱导 Mullins 效应。此外有研究指出，弹性体在长期静载下容易发生不可逆蠕变，而在其产生大形变之后分子链将完成一部分重组和定向排列，提供长效的抗蠕变能力[26]。以上研究从材料力学上印证了预拉伸可以减少弹力链初始力过大带来的不适和潜在风险，同时也能减少弹力链在口腔环境下产生的进一步蠕变，从而提高弹力链的尺寸稳定性和力值稳定性。在最近实验研究中，de Aguiar 等[20]的研究发



Data are expressed as mean ± standard deviation (n = 3, with three independent samples per group; each sample was measured three times and the average value was used for analysis). Intergroup comparisons were performed using repeated measures analysis of variance (ANOVA), with multiple comparisons adjusted by the Bonferroni correction. Compare with the control group, **P < 0.01, ***P < 0.001. In figure a-c, compared with the control group at the same time point; in figure d, compared with the 50% original length pre-stretching for 3 cycles group . The control group did not adopt any pre-stretching, and the parameter settings and experimental grouping of the experimental group are shown in Table 1 and Figure 1, respectively the control group did not adopt any pre-stretching, and the parameter settings and experimental grouping of the experimental group are shown in Table 1 and Figure 1, respectively

Figure 5　Curves of force degradation on each groups of long elastomeric chains

图 5　长距型弹力链对照组及实验组剩余力值变化曲线

现预拉伸处理可以改善弹力链力值急剧衰减的情况；Yang 等[27]与 Pawar 等[28]同样观察到尽管预拉伸会降低弹力链伸长时的初始力，但后续力值衰减幅度更小。此外，Jung 等[21]的研究采用 100% 预拉伸幅度进行 1 ~ 5 次循环，通过分析牙齿移动 1 mm 时的载荷-位移曲线，发现 3 次循环能在模拟牙齿移动过程中保持最高剩余力值，在本研究中同样发现 3 次循环预拉伸组的剩余力值在绝大多数时间点的剩余力值大于其他组。以上研究表明，虽然预拉伸会降低弹力链初始力，但合适的预拉伸可有效减缓弹力链的力值衰减。

3.2　本研究对口腔内环境的模拟

以往对正畸弹力链性能的研究多集中于单一或少数环境变量的影响，如湿度、温度或化学介质中的某一项。然而，口腔实际环境具有多因素协同作用的特点：唾液不仅提供湿润环境[29]，其含有的酶类（如 α-淀粉酶）[22]可能参与材料表面的生物化学过程；此外，唾液作为溶剂体系，可通过溶剂化效应诱导聚合物网络发生膨胀，从而改变弹力链内部的分子链排列与应力分布，进而影响其力学性能[30]。同时，日常饮食导致的温度周期性波动[31]，以及唾液相对稳定的 pH 环境[32-33]，共同影响着弹力链的力学性能。本研究在此基础上，构建了一个集酶活性、动态温度与生理 pH 值的综合模拟系统，将弹力链置于含 α-淀粉酶的人工唾液（pH 值=6.8）中[34]，并进行 5~55 ℃的温度循环。该设计更全面地还原了口腔环境的复杂性，提高了实验结果的临床参考性，也为后续研究提供了可参考的口腔环境模拟方法。在正畸治疗中，预拉伸对弹力链力值变化的影响同样与牙齿移动量密切相关[21]。本研究参考了 Badran 与 Barsoum 的临床数据，Badran 等[35]在临床研究中发现当弹力链施加持续力辅助关闭间隙时，实验组 6 周时间隙平均关闭 1.97 mm，Barsoum 等[36]的研究发现在弹力作用于尖牙内收时，尖牙每月平均移动距离为（0.86±0.14）mm。基于此，本研究将弹力链固定装

置间距设置为每周减少0.35 mm，以模拟正畸临床中牙齿的渐进性移动。此外，本研究中初始力值的选择兼顾了力学效率与组织安全性。研究指出，在无摩擦条件下，约100 g的力值可能更利于尖牙的远中移动，而过高的力（如＞150 g）则可能对牙周组织不利[37]。然而，临床实际中存在因托槽−弓丝摩擦导致的力值损耗[38-39]，故本研究将对照组初始力值设定为150 g，旨在近似真实负荷下评估弹力链的力学性能变化。

3.3 牙齿移动对弹力链剩余力值的影响

有研究在体外研究中测得弹力链四周时力值衰减为初始力值的44.4%±8%[40]，另一项研究将弹力链的体内和体外力值衰减量进行比较，发现体内组的力值衰减大于体外实验组[41]。一些学者[42-43]进行了弹力链力学衰减的口内研究，发现1周时口内组力值衰减明显大于口外模拟口内环境组，3周时口内组剩余力仅为初始力的25%～27%，可能是牙齿在力的作用下持续移动导致弹力链的拉伸长度不断减小[44]。而本实验中两种连接体类型弹力链对照组在模拟牙齿移动情况下3周时剩余力值平均值为（45.50±1.57）g、（46.90±2.3）g，分别仅为初始力值的30.33%±1.05%、31.27%±1.56%，与其研究结果接近。

将本研究两种类型弹力链的对照组及最优预拉伸组（50%原长度3次）在关键时间点（7、14、21、28 d）的剩余力值进行比较，结果显示在7、14、21 d时，与多数文献报道一致[45-46]，紧密型弹力链对照组的剩余力值大于长距型弹力链；当两种类型弹力链同时按最优处理进行50%原长度预拉伸3次时，紧密型弹力链以上时间点的剩余力值依然更大。只有28 d时（累计模拟牙齿移动1.4 mm后），无论是否经过最优预拉伸处理，长距型弹力链的剩余力值均显著高于紧密型（对照组与50%原长度预拉伸3次组）。其机制在于“相对形变率”的差异，当两种链型被拉伸至相同初始力值时，长距型链的原始长度更大。在后续每周相同的绝对缩短量（模拟牙齿移动）下，长距型弹力链的相对形变率始终小于紧密型弹力链。这说明随着牙齿移动的持续进行，长距型弹力链承受的周期性应变刺激更弱，其固有应力松弛劣势，逐渐被“低应变刺激”的力学优势所抵消乃至逆转。然而，临床正畸治疗中，单次复诊周期内的牙齿移动量确有生理极限（通常约1~2 mm/月）[35-36]。因此，在绝大多数以单次加力为目标的常规临床使用中，紧密型弹力链依然能展现更好的力学性能。

3.4 本研究的临床意义

在本研究中，所有的预拉伸处理都降低了弹力链的初始力值，而在7、14、21、28 d时间点，紧密型弹力链和长距型弹力链重复预拉伸50%原长度3次的剩余力值比对照组及其余实验组剩余力值大。这表明，经合理预拉伸处理的弹力链，其初始力值得以适度降低以避免患者疼痛不适及牙根吸收风险，而中后期（7~28 d）的力值维持水平却显著提升，从而有望在不增加初始创伤的前提下，延长弹力链的有效作用时间，减少复诊频率。本研究的意义在于首次系统比较了同一品牌下两种常用类型（紧密型与长距型）弹力链的预拉伸效果，并明确了预拉伸50%原长度3次能更好地延缓其力值衰减。这为临床医生在使用该品牌或具有类似材料特性的产品时，提供了一种明确、可操作的预拉伸方案，旨在通过简单的椅旁预拉伸操作来提升矫治效率。未来研究可纳入更多品牌，以验证本结论的普适性并探索品牌间的交互效应。

3.5 本研究的局限性及未来展望

本研究通过体外模拟，在控制温度、唾液化学环境与周期性牙齿移动的条件下，评估了不同预拉伸方式对弹力链力值衰减的影响。然而，本研究模型虽引入了关键的温度与化学因素，但未涵盖口腔内全部动态生理环境。其次，本研究关于牙齿移动距离设定的局限性在于采用了恒定距离模拟牙齿每周移动（0.35 mm）。这一简化模拟虽便于在体外条件下进行不同预拉伸方式的互相比较，但未能完全模拟临床实际。此外，尽管有文献指出不同品牌弹力链的预拉伸效应可能无显著差异[18]，但不同品牌在原材料、制造工艺上仍可能存在区别，这些都可能影响其力学性能与对预拉伸的反应。未来研究时应构建微生物环境及唾液流动的体外环境，在现有力学数据基础上，结合骨改建生物学理论，建立“力−位移−时间”动态仿真模型，模拟在持续衰减的力值作用下牙齿移动速率的真实变化，以形成从体外机理到临床效能的进一步转化。

4 结 论

预拉伸会降低弹力链的初始力值，使力值变化更趋平缓，从而实现正畸治疗中初始力与持续轻力之间的平衡；采用合适的预拉伸方法能有效减缓弹力链的力值衰减；相对而言，以50%原长度

进行3次预拉伸能最大程度延缓弹力链的力值衰减。

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