Supplementary Information

Establishing direct relationships between soft material perception and rheology

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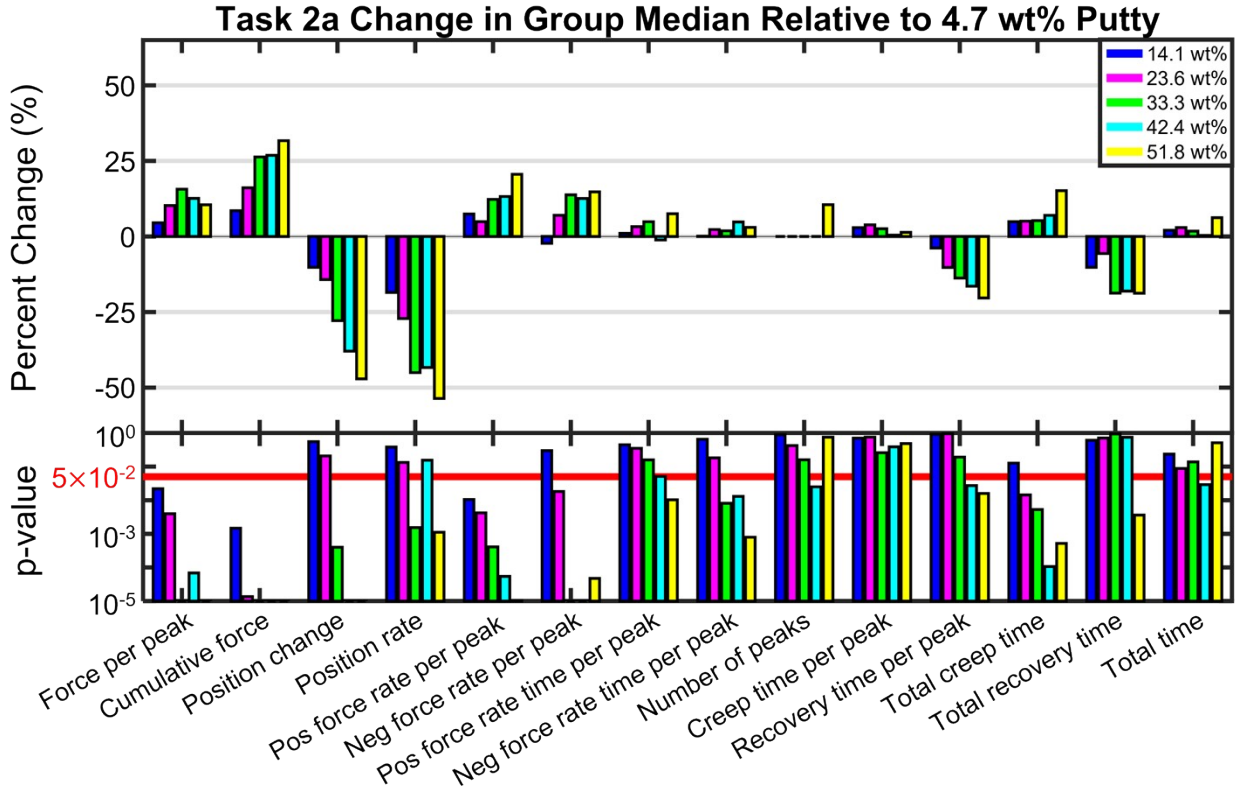
Defined term	Definition	Rheological meaning
Force	Maximum force applied per peak	Stress
Position	Distance from the sensor to the putty; how far a user has pressed into a sample	Strain
Creep time	How long, per peak, the force is applied to the sample	Time
Recovery time	How long, per peak, the material is allowed to elastically recover prior to receiving more force	Time
Positive Force Rate	The maximum, per peak, of the first derivative of force with respect to time	Stress rate
Negative Force Rate	The minimum, per peak, of the first derivative of force with respect to time	Stress rate
Positive Force Rate Time	How long a positive force rate peak is applied for	Time
Negative Force Rate Time	How long a negative force rate peak is applied for	Time
Number of peaks	How many distinct force peaks are applied to a sample	Number of stress maxima applied in a rheological test, such as a frequency sweep
Total Creep time	How much creep time an individual uses per sample	Time
Total Recovery time	How much recovery time an individual uses per sample	Time
Total Exploration time	How much time an individual overall per sample	Time
Cumulative Force	The integral of force with respect to time per sample	Integral of stress with respect to time
Position Rate	The rate at which someone presses into a sample	Strain rate

Definition of terms used in this work

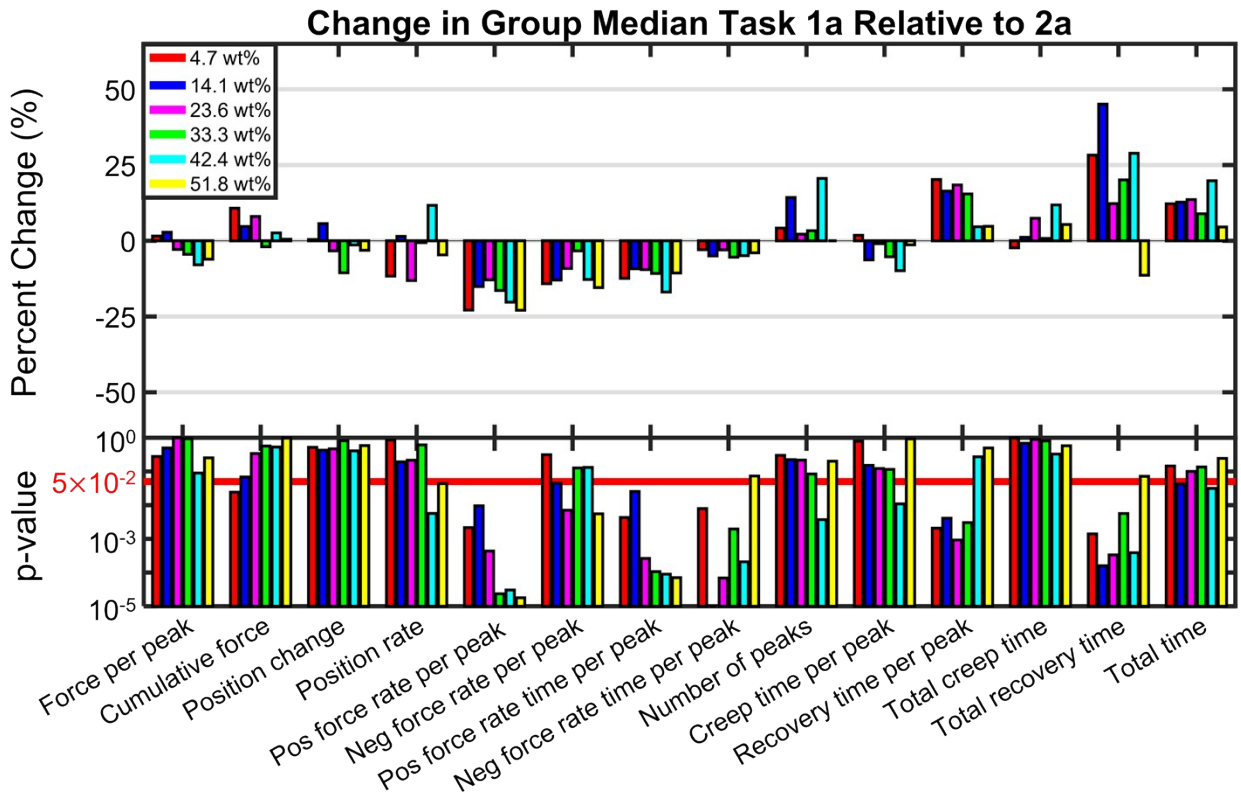
Supplementary Table 1. Definition of terms used to characterize sensory data. While comparing samples in the sensory tests, sensors measured force and position data as a function of time. From this data, 14 terms were defined to quantify their behaviors such that they have clear rheological meaning.

Behavioral differences between tasks – Statistical comparison

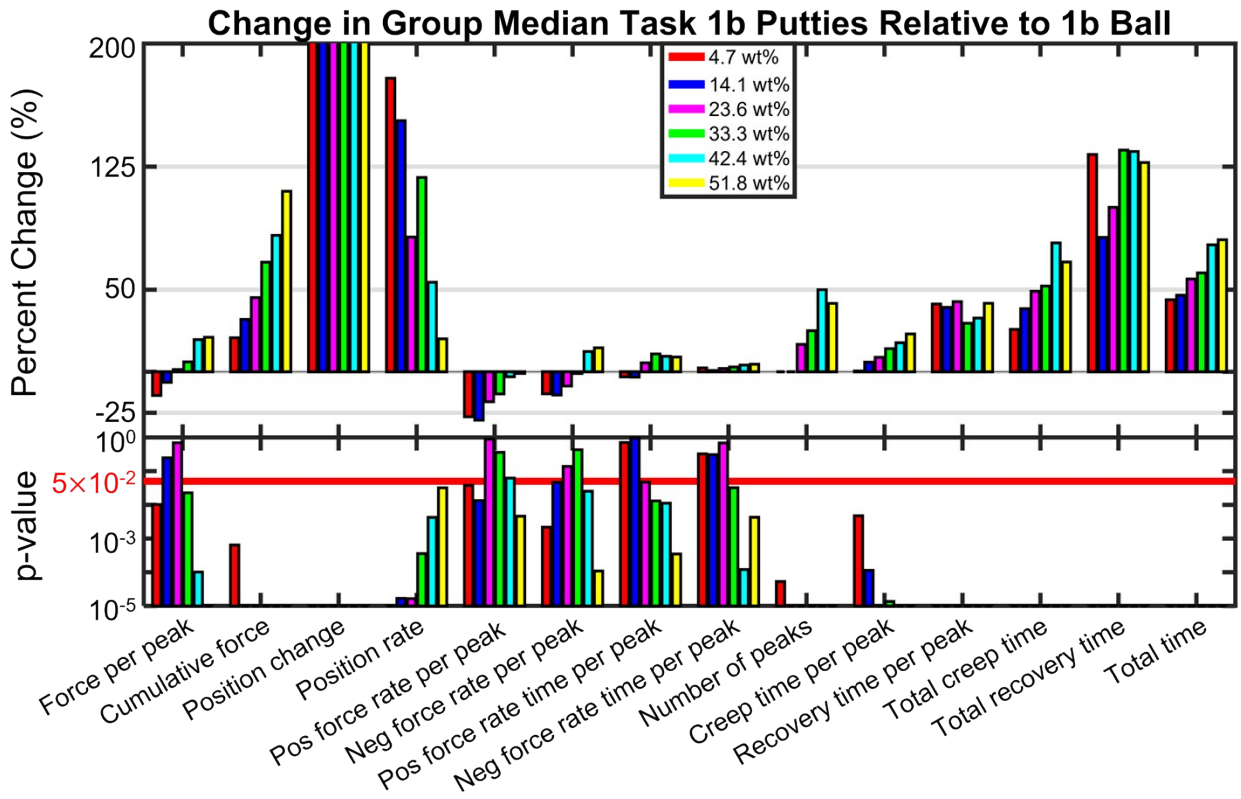
In the sensory testing, subjects were asked to complete several tasks. In Task 1a, subjects unknowingly compared two identical putties to determine which was firmer. In Task 2a, they repeated Task 1a while wearing a plastic finger cover to restrict cutaneous feedback. In Task 1b, they compared putties with an obviously different material, a solid rubber ball. In Task 2b, they repeated Task 1b while wearing a plastic finger cover to restrict cutaneous feedback. Supplementary Figures 1 – 10 highlight the statistical differences in user behaviors throughout the tasks, in the same way as Figure 3. The variables used are defined in Supplementary Table 1.



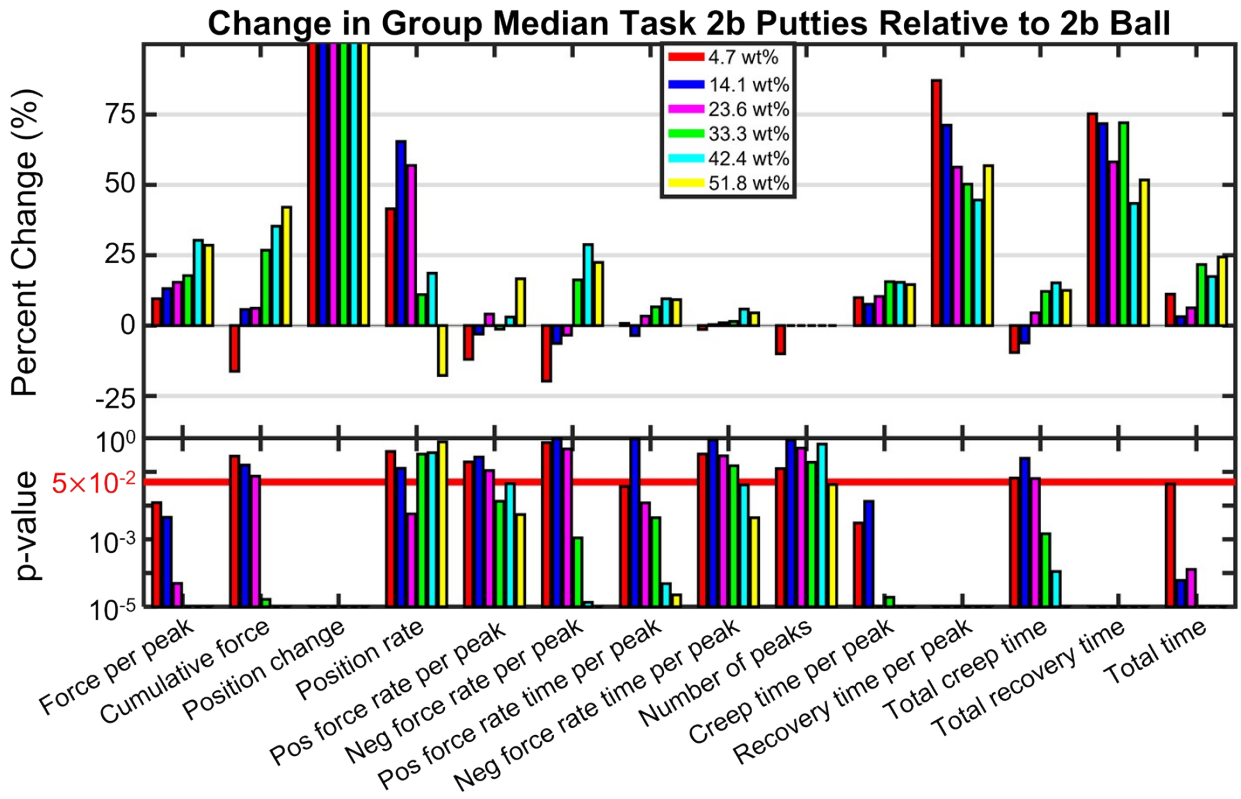
Supplementary Figure 1 – Concentration dependent behavior in Task 2a. Despite the loss of cutaneous feedback, subjects still apply more force as hardener concentration increases and experience less deformation. Differences in amounts of time used are minimal.



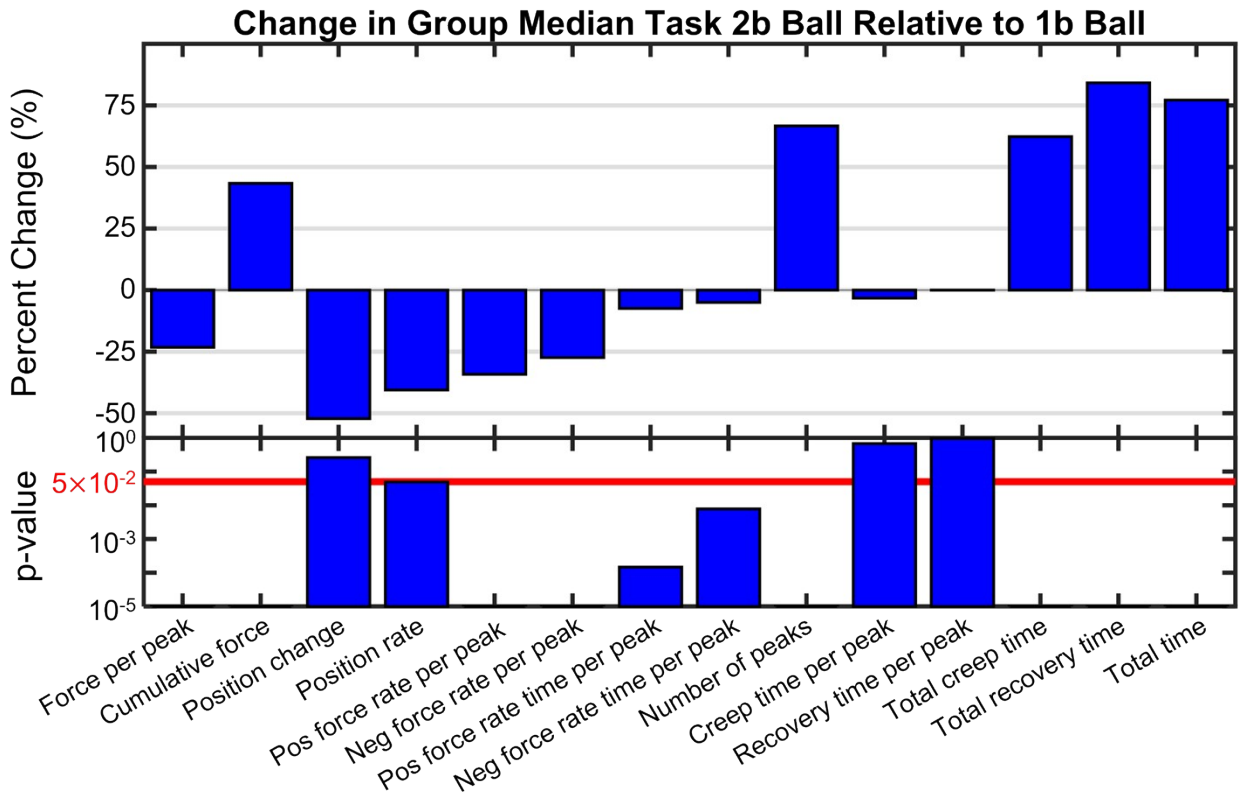
Supplementary Figure 2 – Differences in behavior from Task 2a relative to Task 1a. Without cutaneous feedback, subjects appear to apply force at lesser rates and use more recovery time.



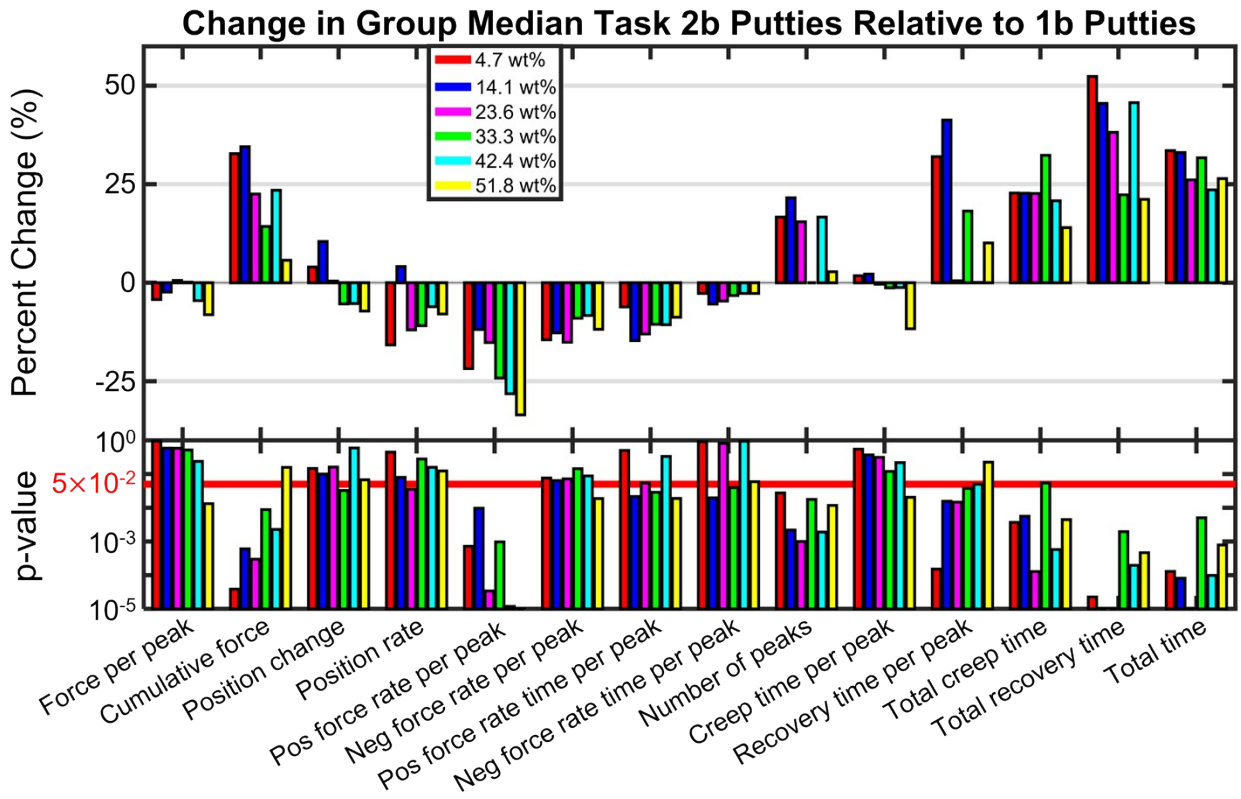
Supplementary Figure 3 – Behavioral differences between touching the putties versus the ball in Task 1b. Subjects interact with the putties significantly different than the ball. While the used force and force rate are approximately equal, subjects spent significantly more time on the putties. Since the position change is ≈ 0 for the ball, the relative position change is infinite.



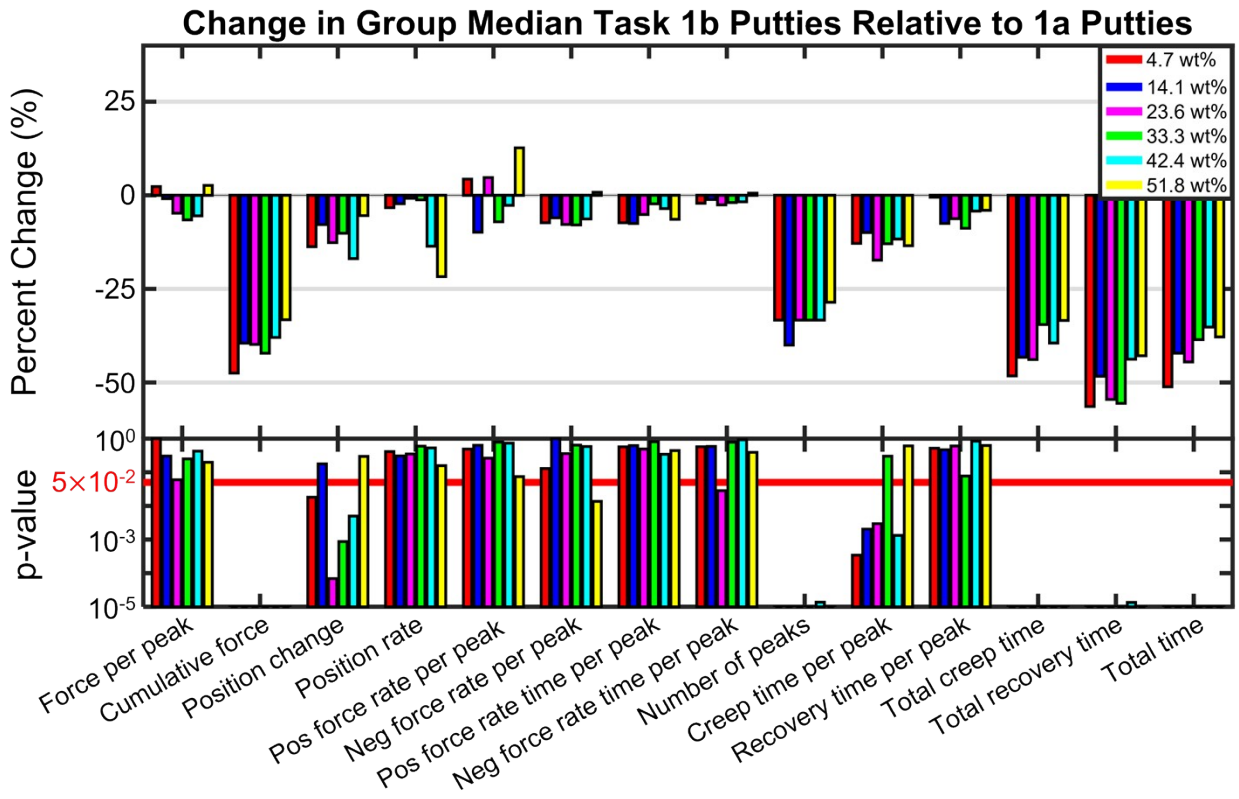
Supplementary Figure 4 – Behavioral differences between touching the putties versus the ball in Task 2b. Like Task 1b, subjects probe the putties significantly different than the ball. Subjects appear to use more force with increasing concentration and much more recovery time, but minimal change in the number of peaks and little change in creep time.



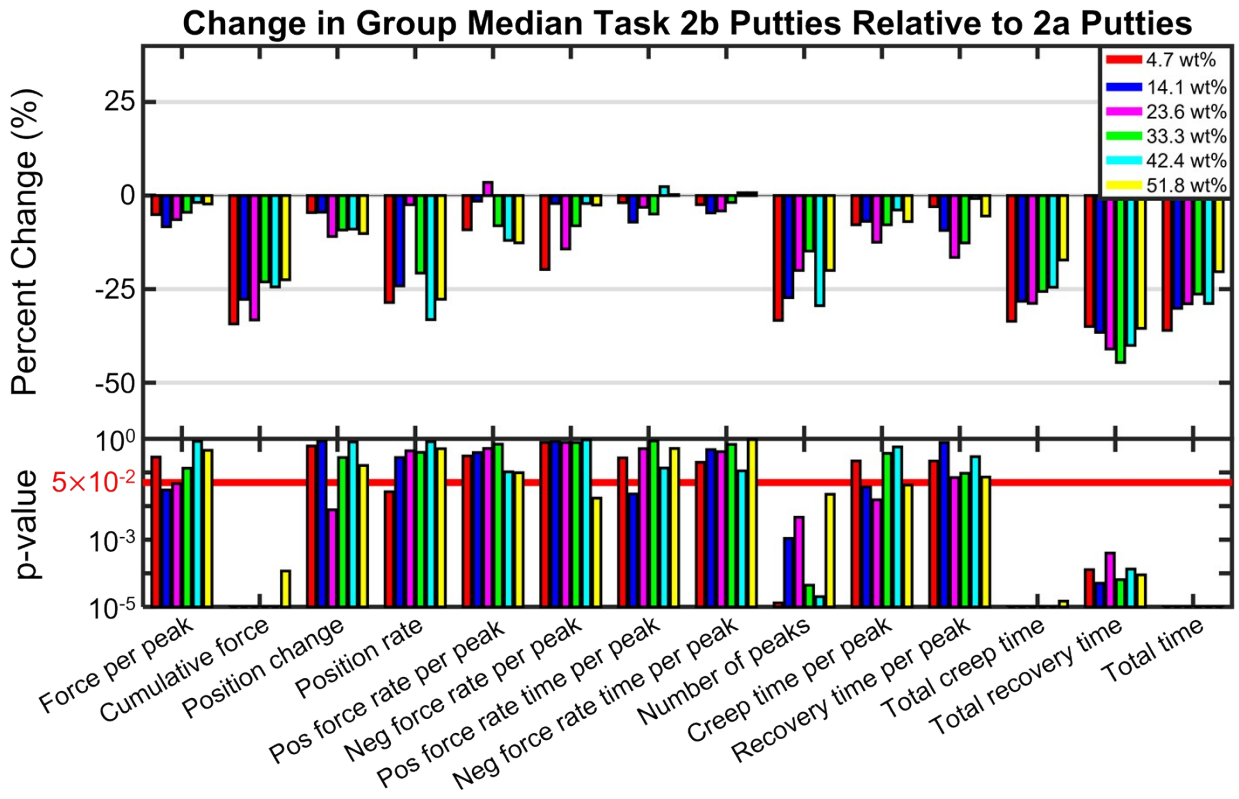
Supplementary Figure 5 – Behavioral differences when touching the ball in Task 2b relative to 1b. Without cutaneous feedback, subjects appear to use less force per peak, but more force cumulatively due to spending significantly more time on the sample.



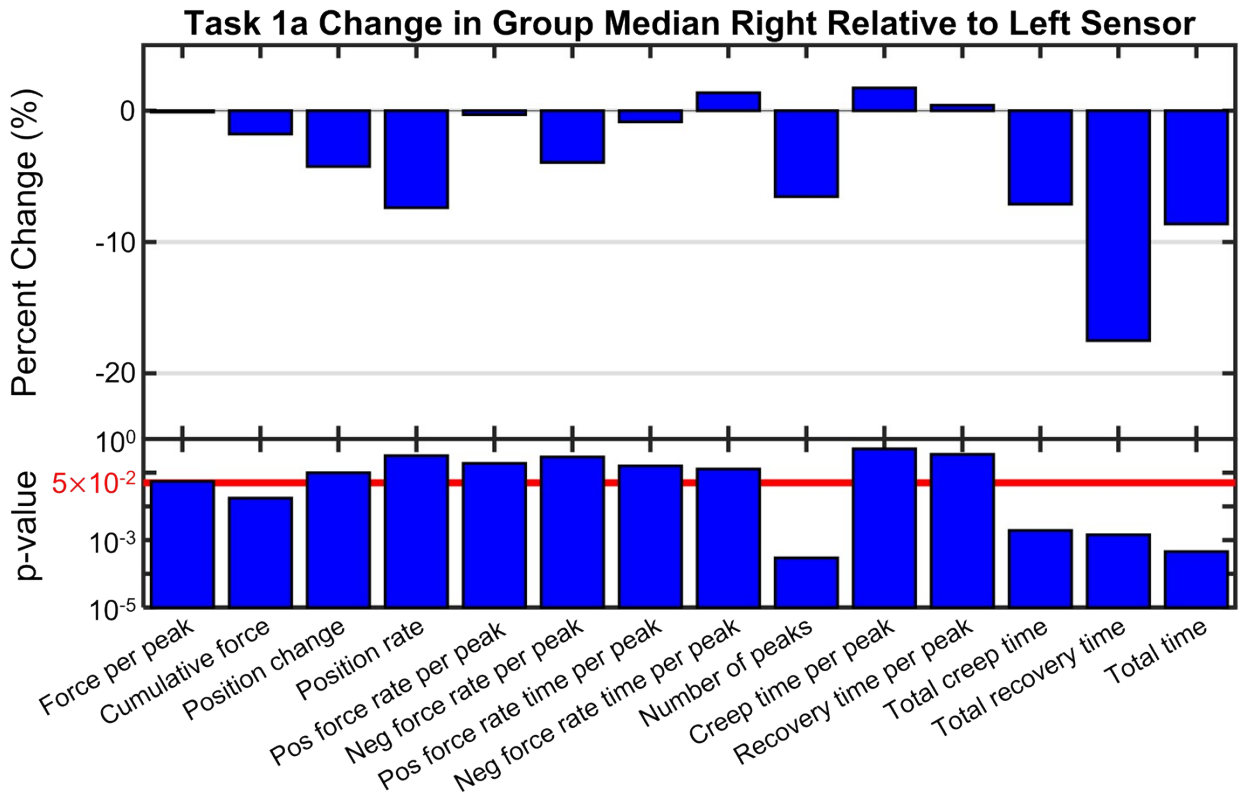
Supplementary Figure 6 – Behavioral differences when touching the putties in Task 2b relative to 1b. Without cutaneous feedback, the subjects behave differently despite touching the same materials. There is minimal change in the applied force, but subjects spend significantly more time on each sample.



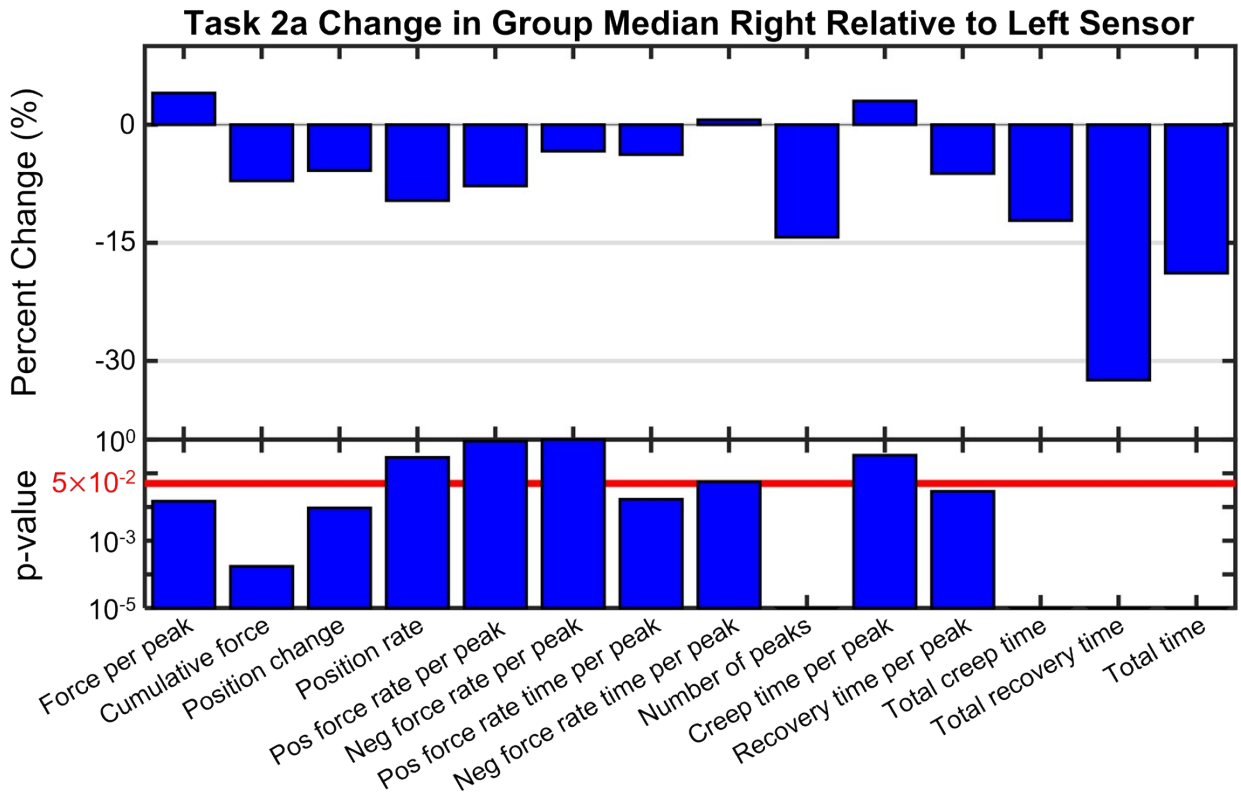
Supplementary Figure 7 – Comparison of behavior across tasks with cutaneous feedback. Subjects behave differently when the tasks are of differing difficulty. When probing the same materials, subjects used approximately the same amount of force, but spent significantly less time on each sample when the material they were comparing to was noticeably different.



Supplementary Figure 8 – Comparison of behavior across tasks without cutaneous feedback. Subjects behave differently when the tasks are of differing difficulty. When comparing the same materials, subjects used approximately the same amount of force but significantly less time when the material they were comparing to was noticeably different.



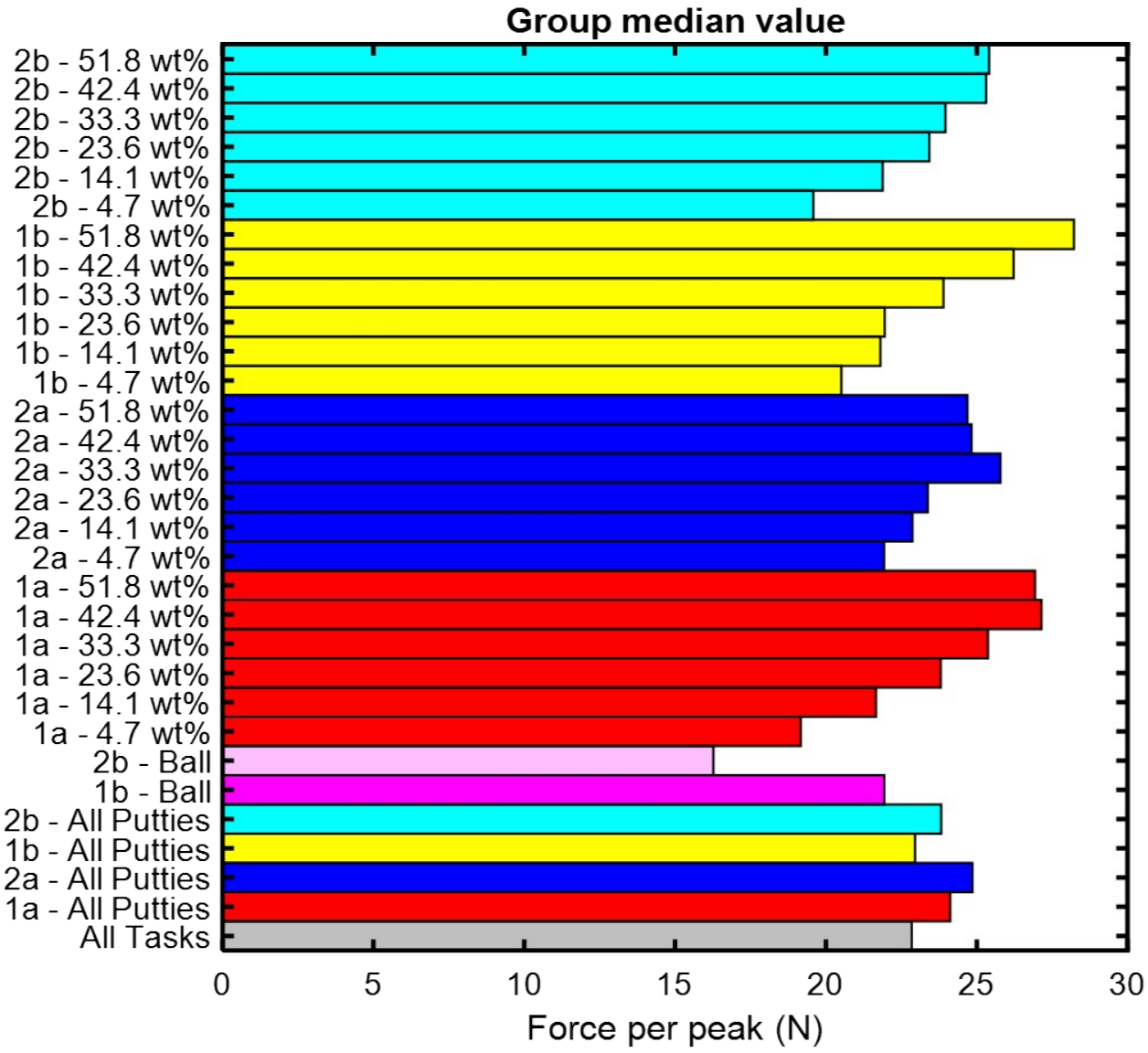
Supplementary Figure 9 – Difference in behaviors between each sensor in Task 1a. The materials on the left and right sensors are identical. Since subjects probed the left sample first, it was of interest to see if they behaved differently when examining the right sensor. Subjects appear to use slightly less time when examining the sample on the right sensor.



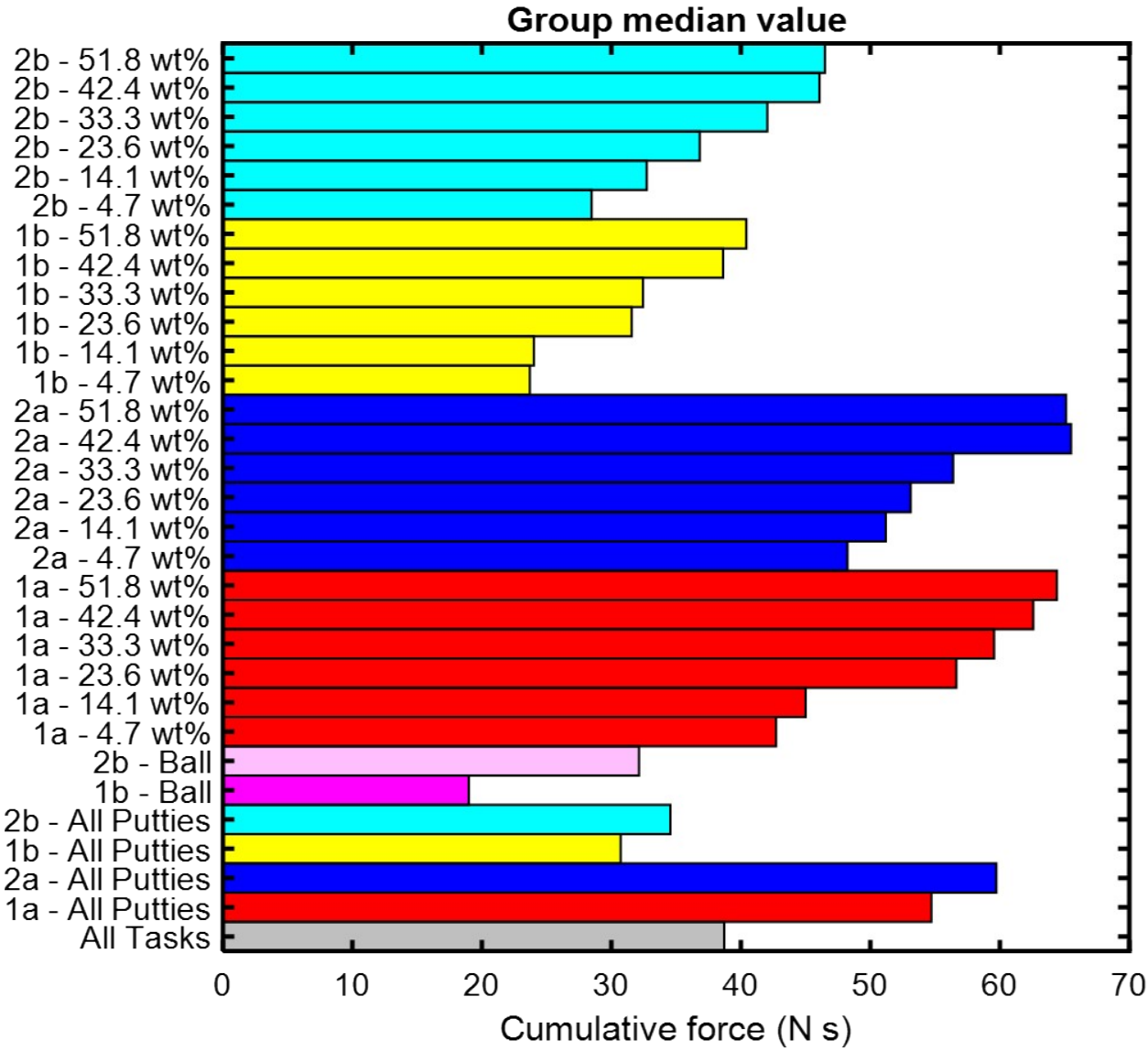
Supplementary Figure 10 – Difference in behaviors between each sensor in Task 2a. The materials on the left and right sensors are identical. Since subjects probed the left sample first, it was of interest to see if they behaved differently when examining the right sensor. Subjects appear to use slightly less time when examining the sample on the right sensor. The difference appears slightly larger without cutaneous feedback.

Behavioral differences between tasks – Absolute comparison

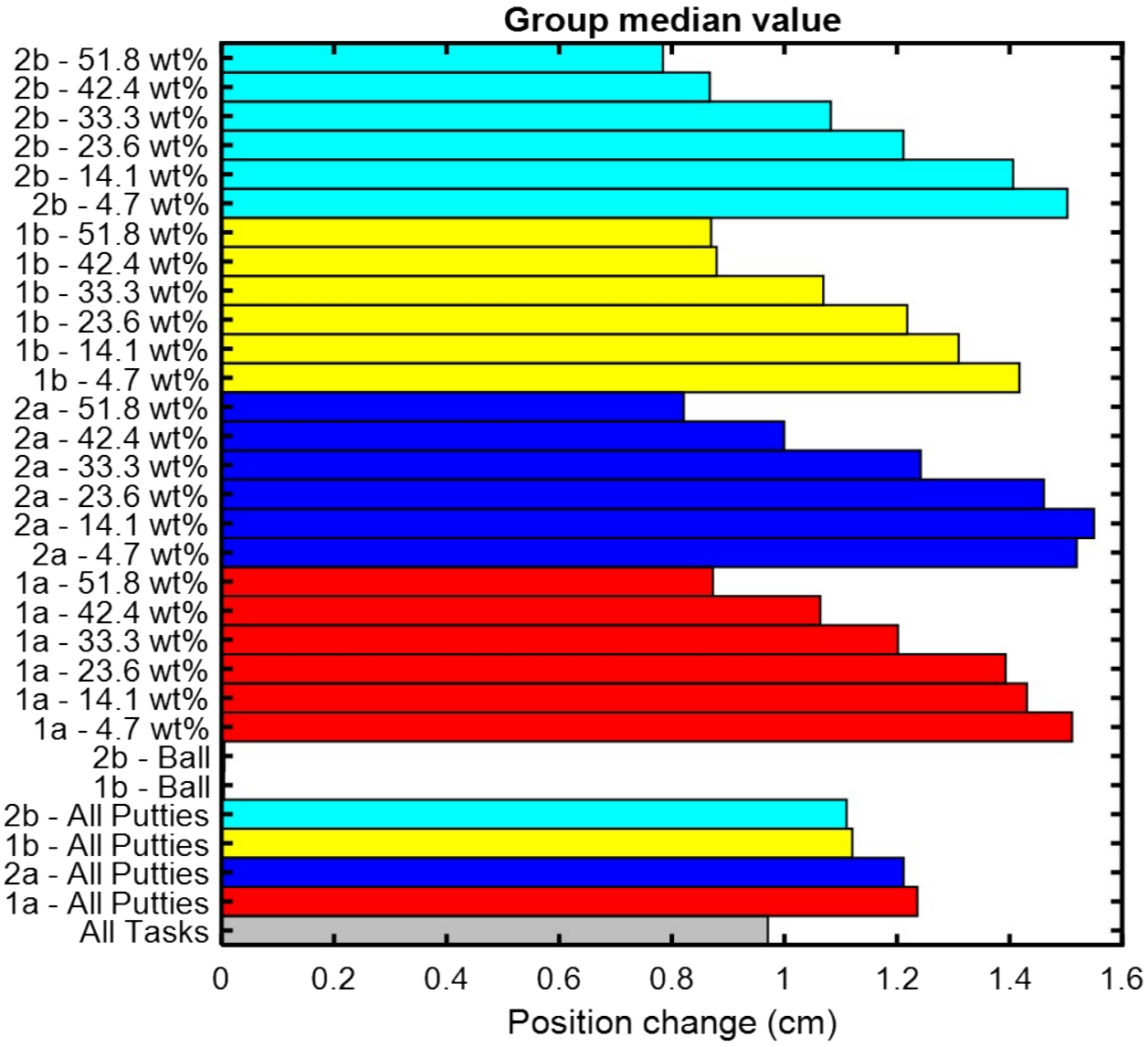
While relative changes in behavior are interesting to understand how people behave in different scenarios, it is also important to know absolute measures so that they can be used to design rheological tests. The median behavior of the group is reported for each of the 14 defined terms.



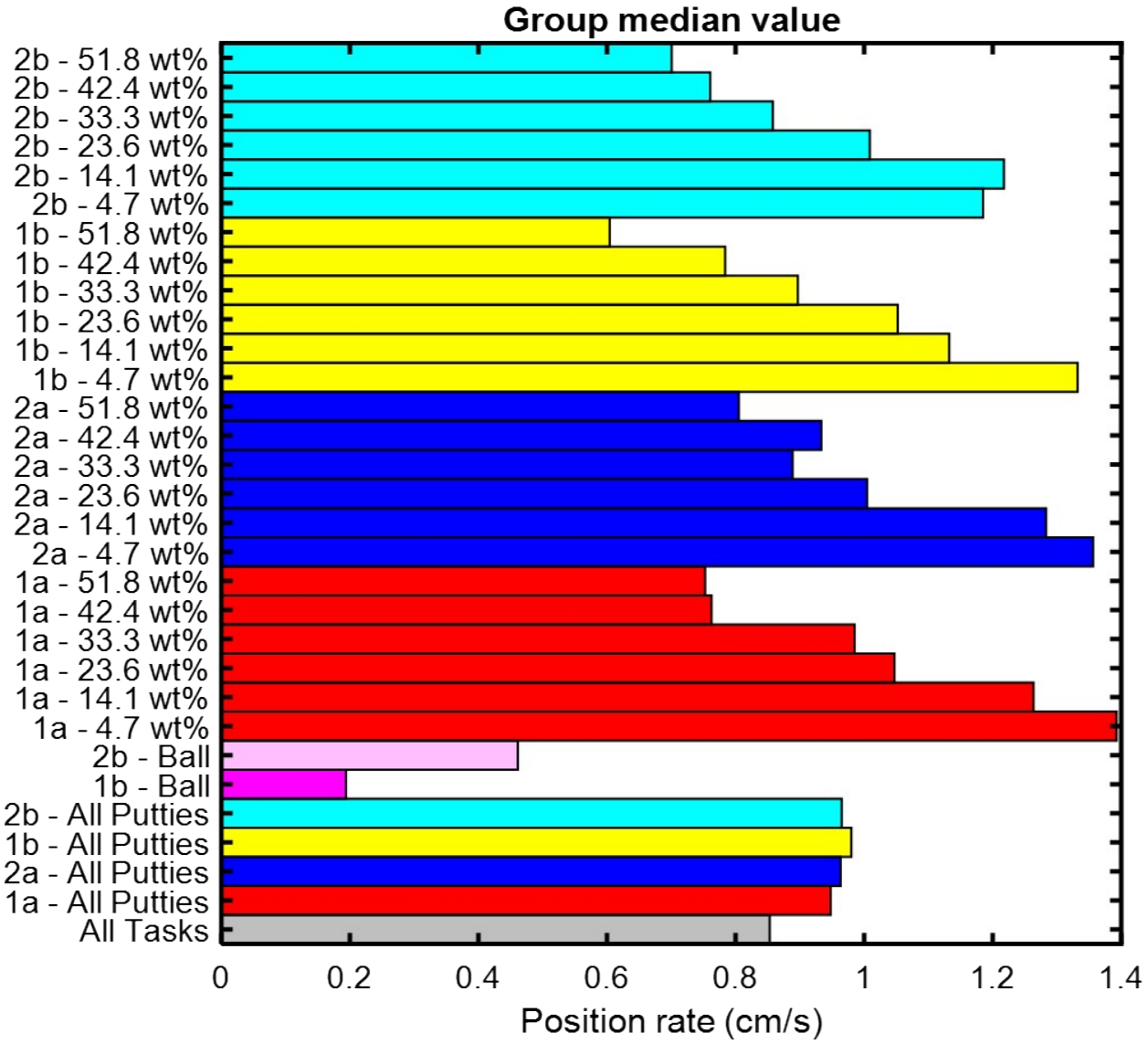
Supplementary Figure 11 – Median force per peak applied by the group in different tasks.



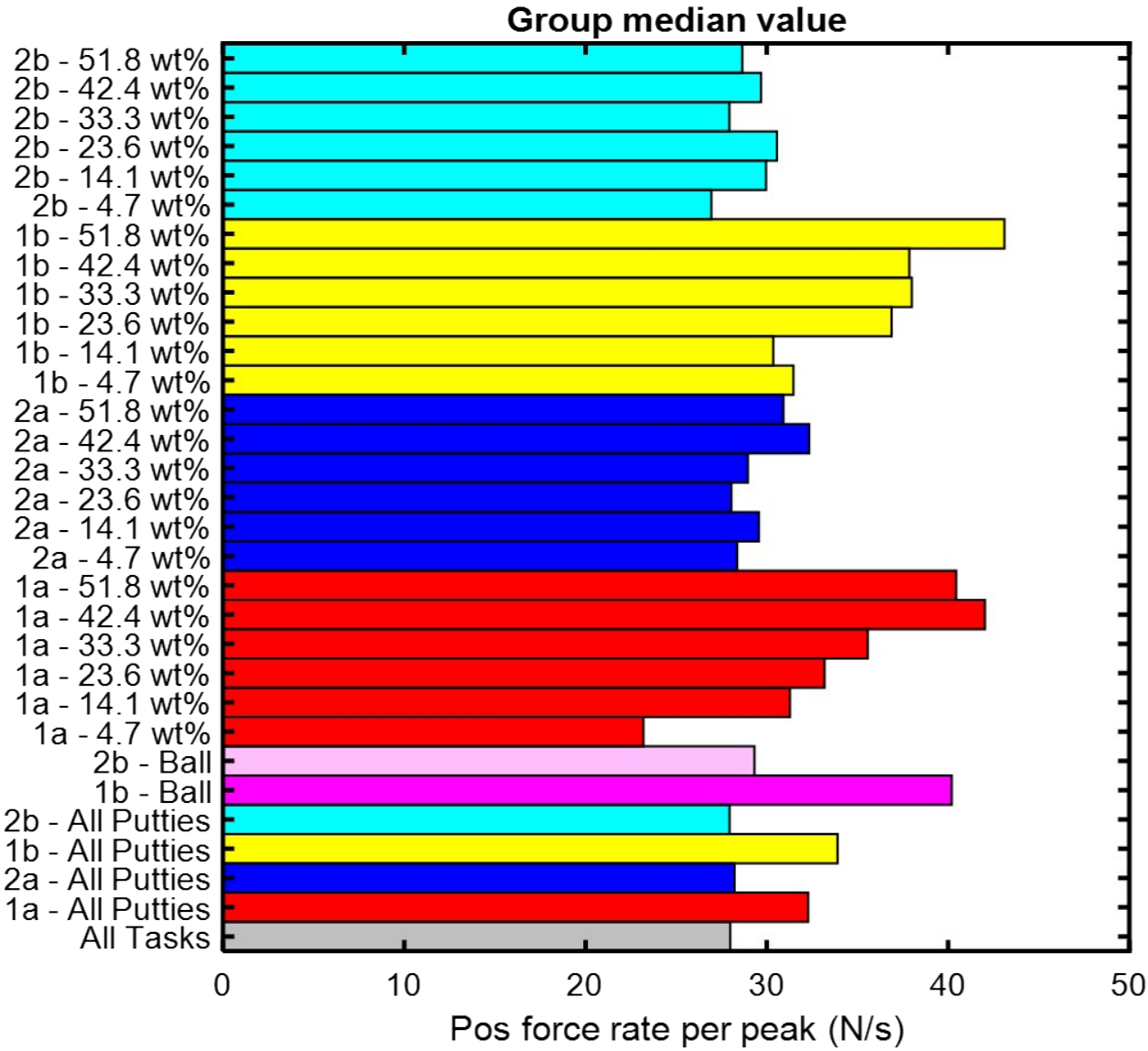
Supplementary Figure 12 – Median cumulative force applied by the group in different tasks.



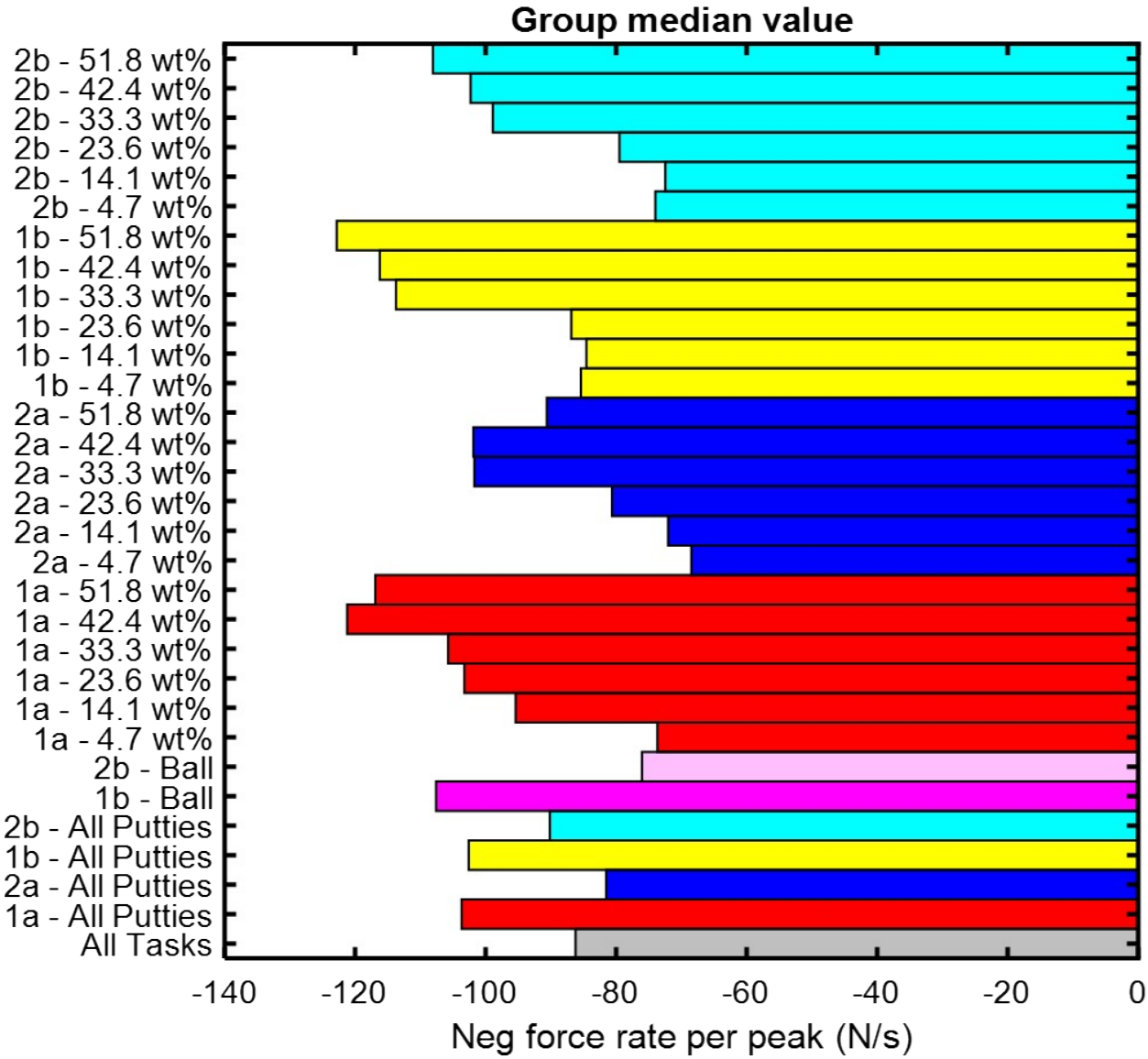
Supplementary Figure 13 – Median position change applied by the group in different tasks.



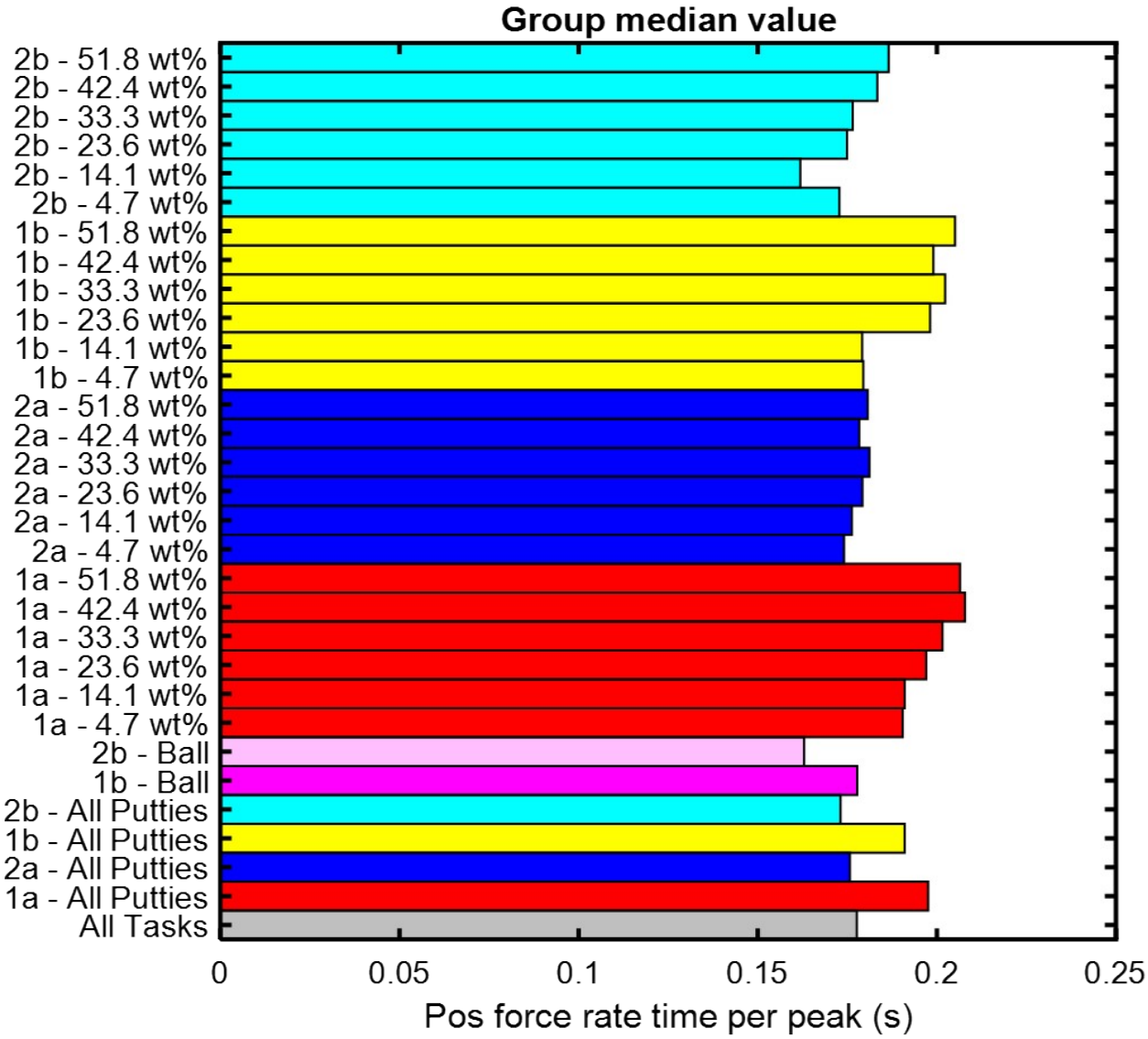
Supplementary Figure 14 – Median position rate applied by the group in different tasks.



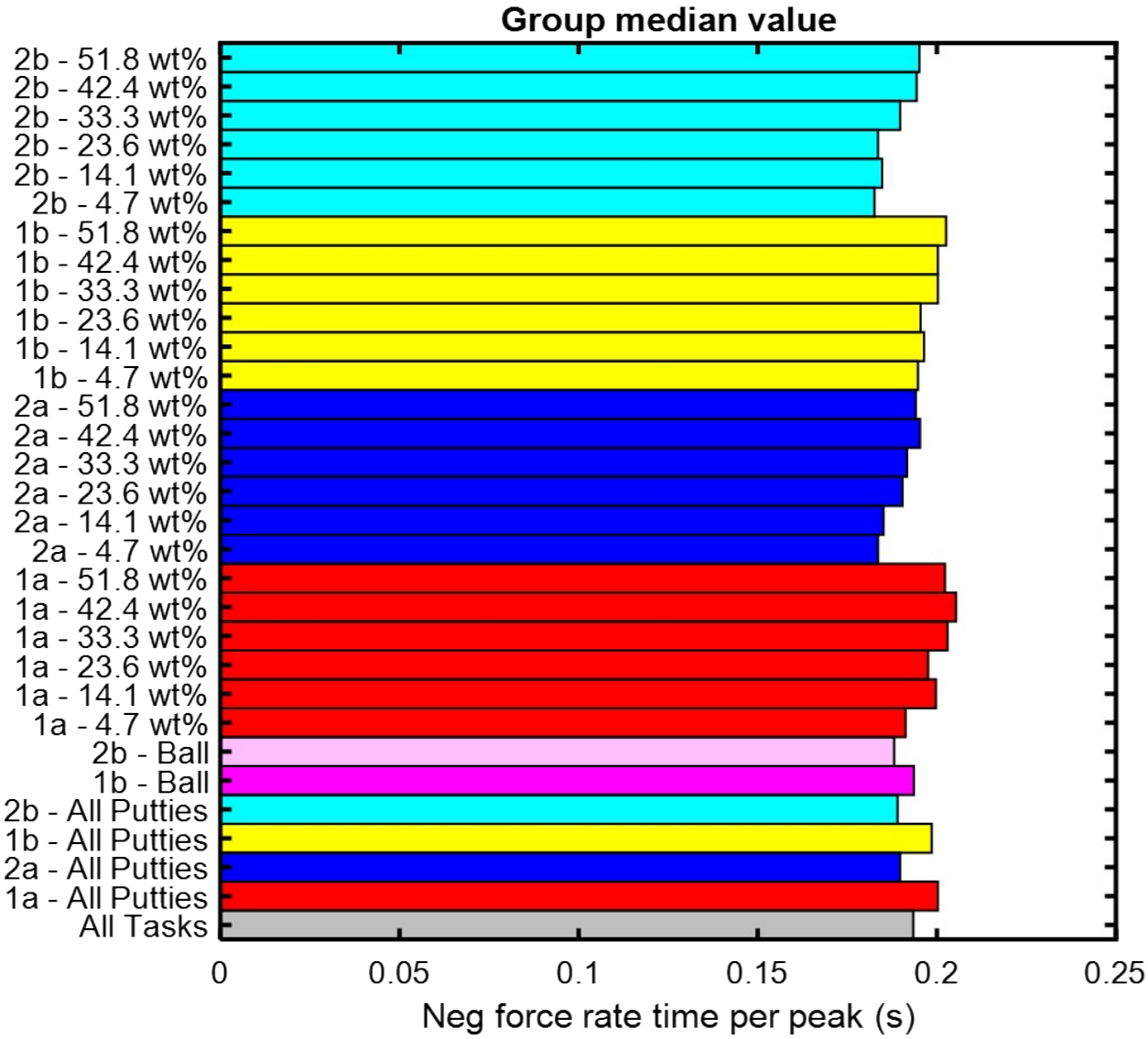
Supplementary Figure 15 – Median positive force rate applied by the group in different tasks.



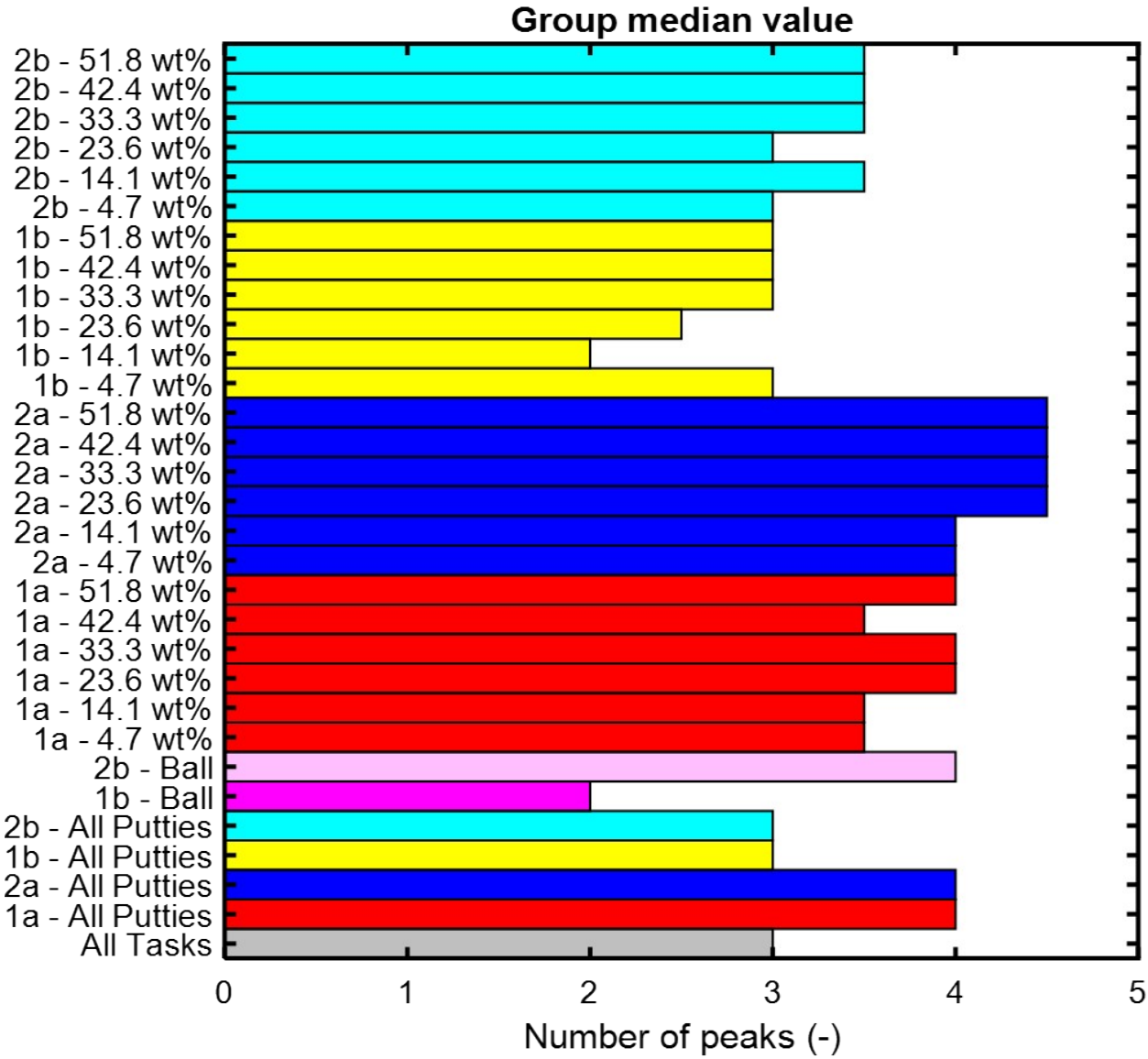
Supplementary Figure 16 – Median negative force rate applied by the group in different tasks.



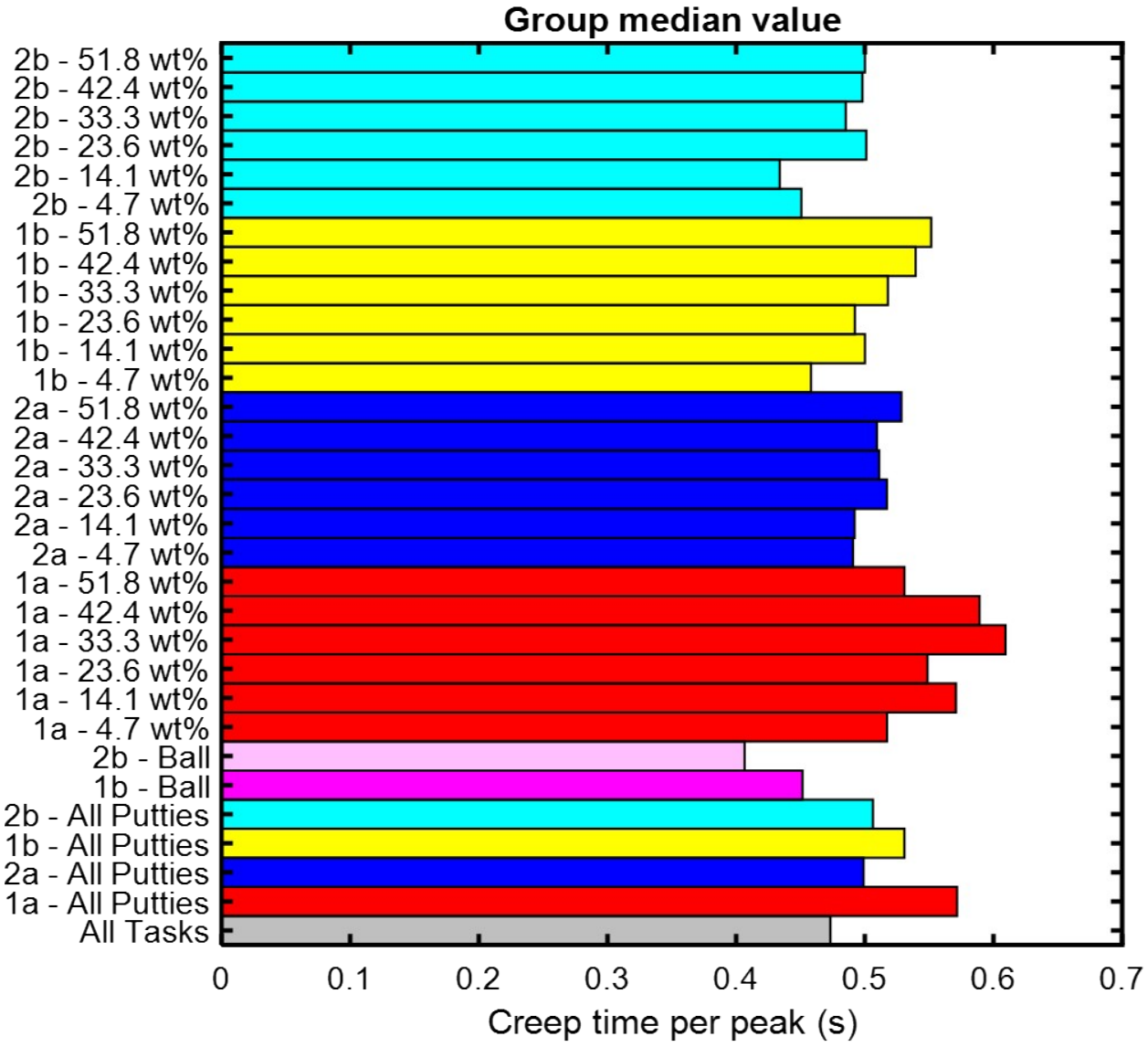
Supplementary Figure 17 – Median time of a positive force rate peak applied by the group in different tasks.



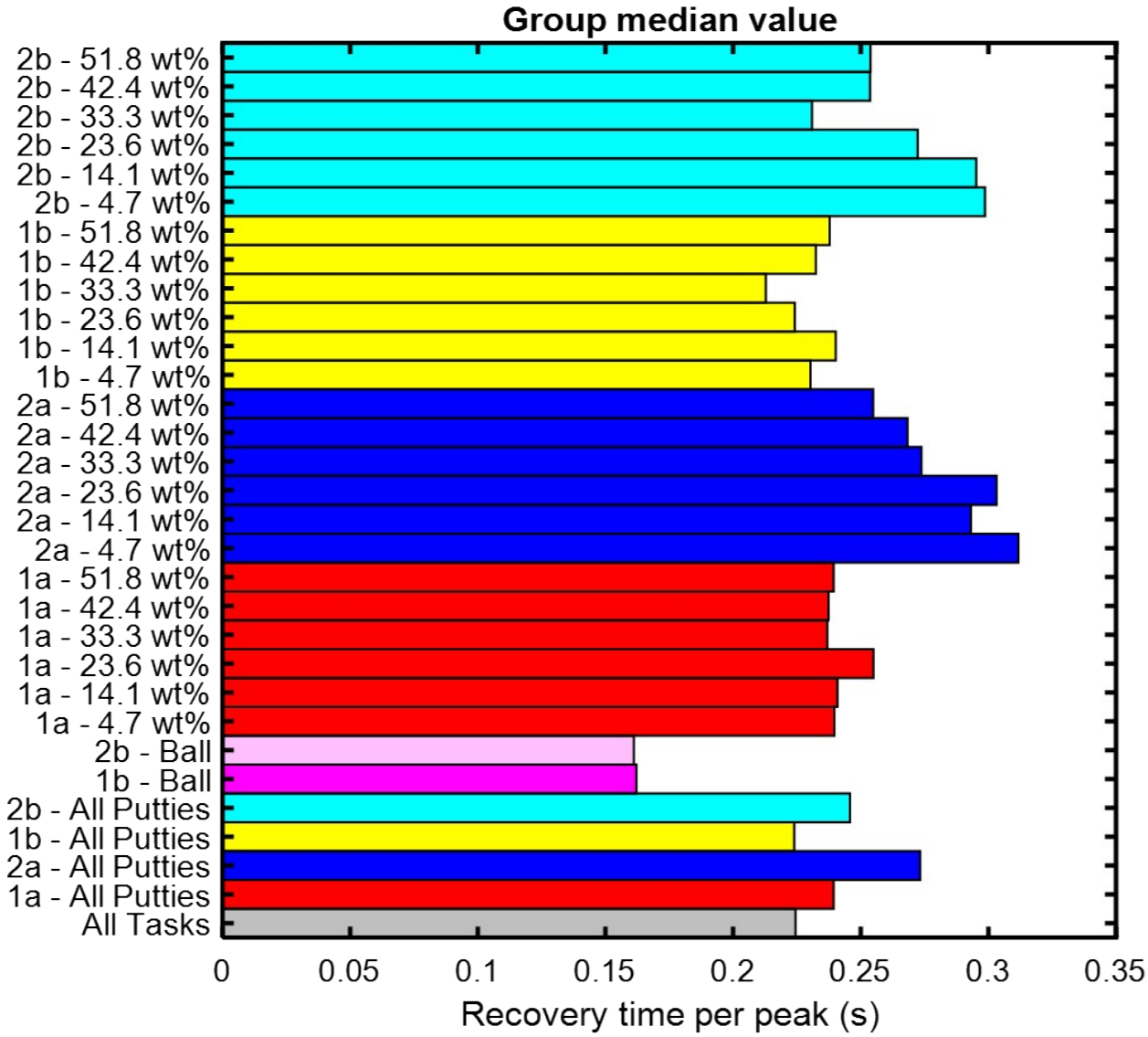
Supplementary Figure 18 – Median time of a negative force rate peak applied by the group in different tasks.



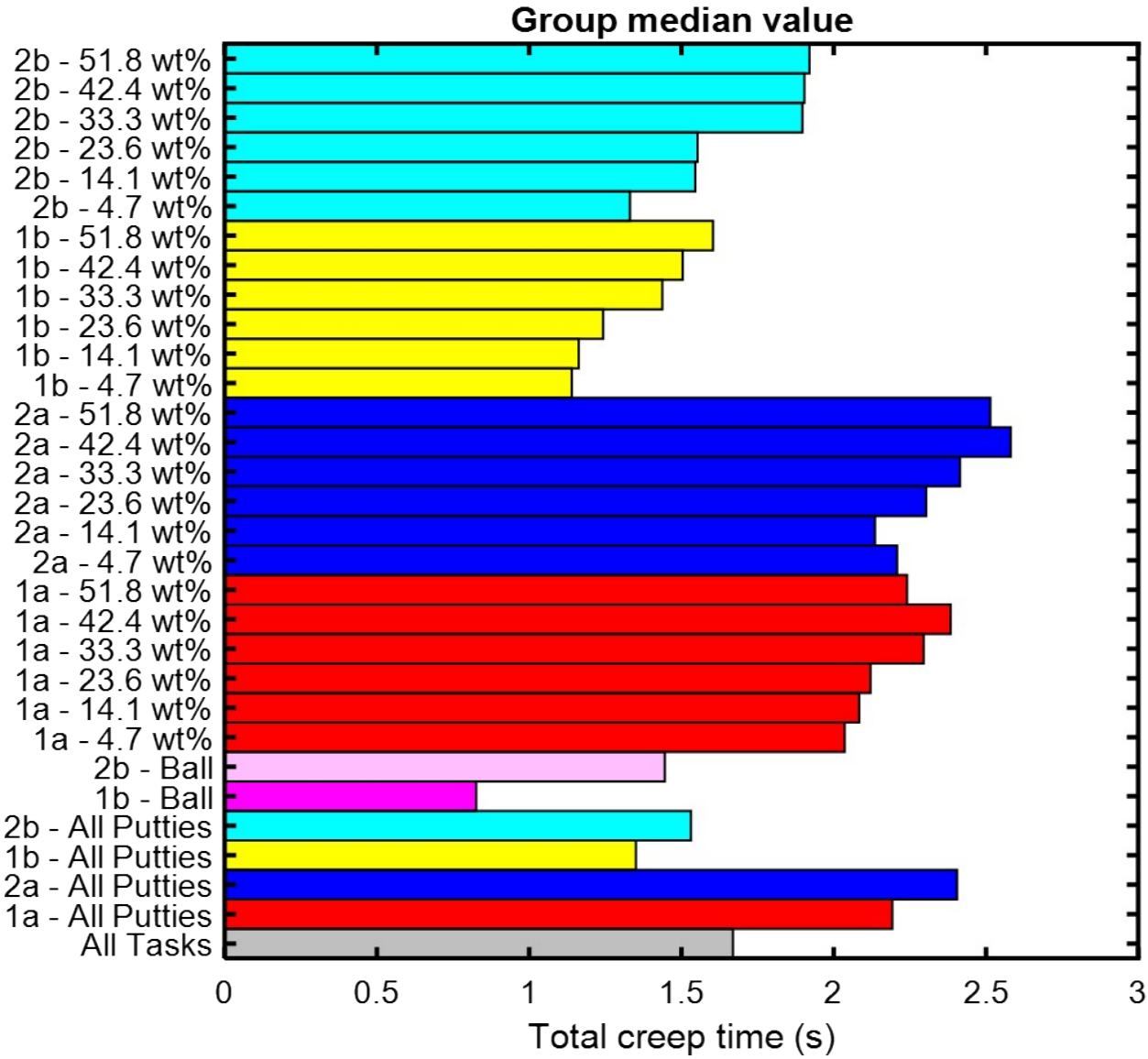
Supplementary Figure 19 – Median number of peaks applied by the group in different tasks.



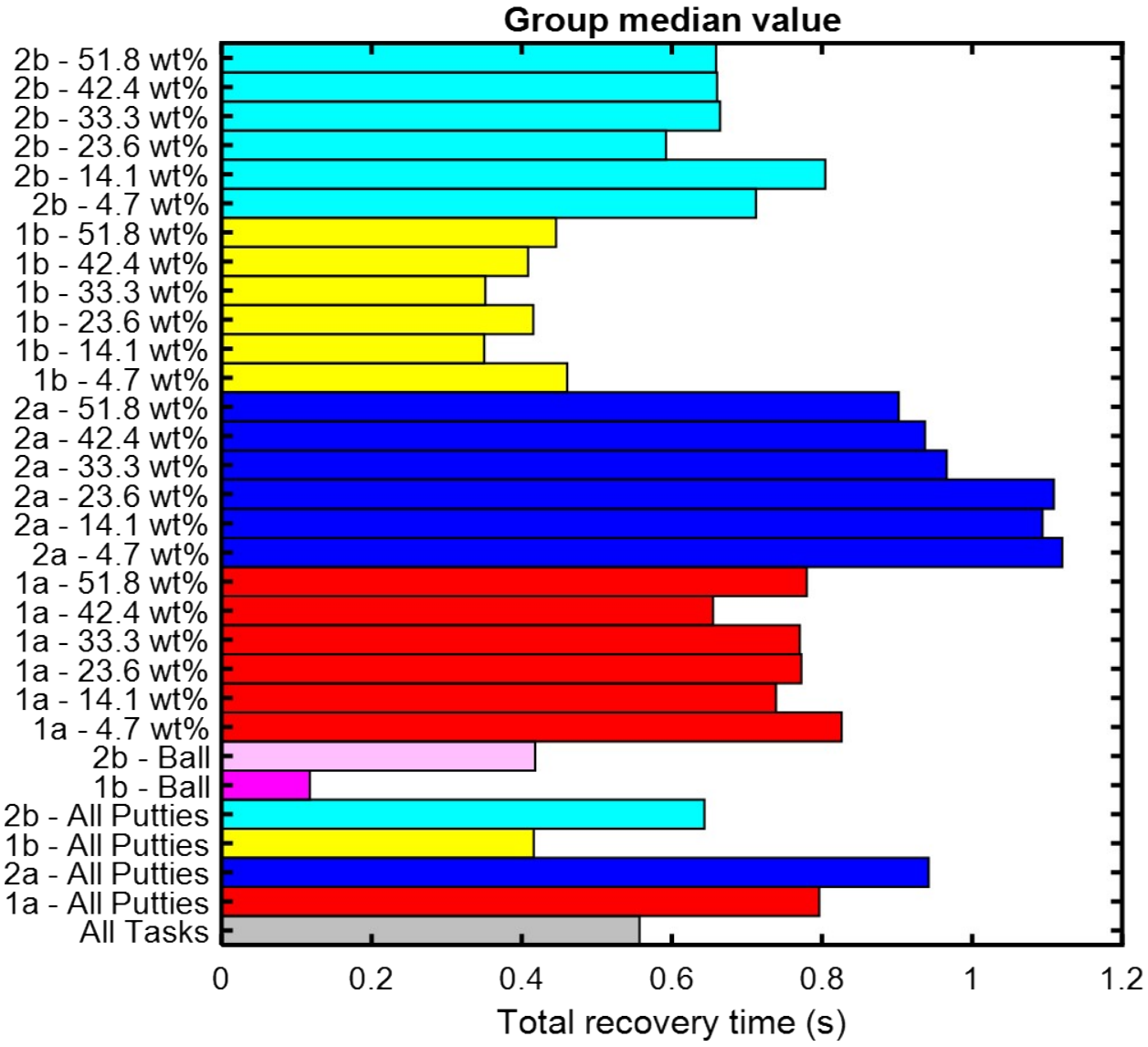
Supplementary Figure 20 – Median creep time per peak applied by the group in different tasks.



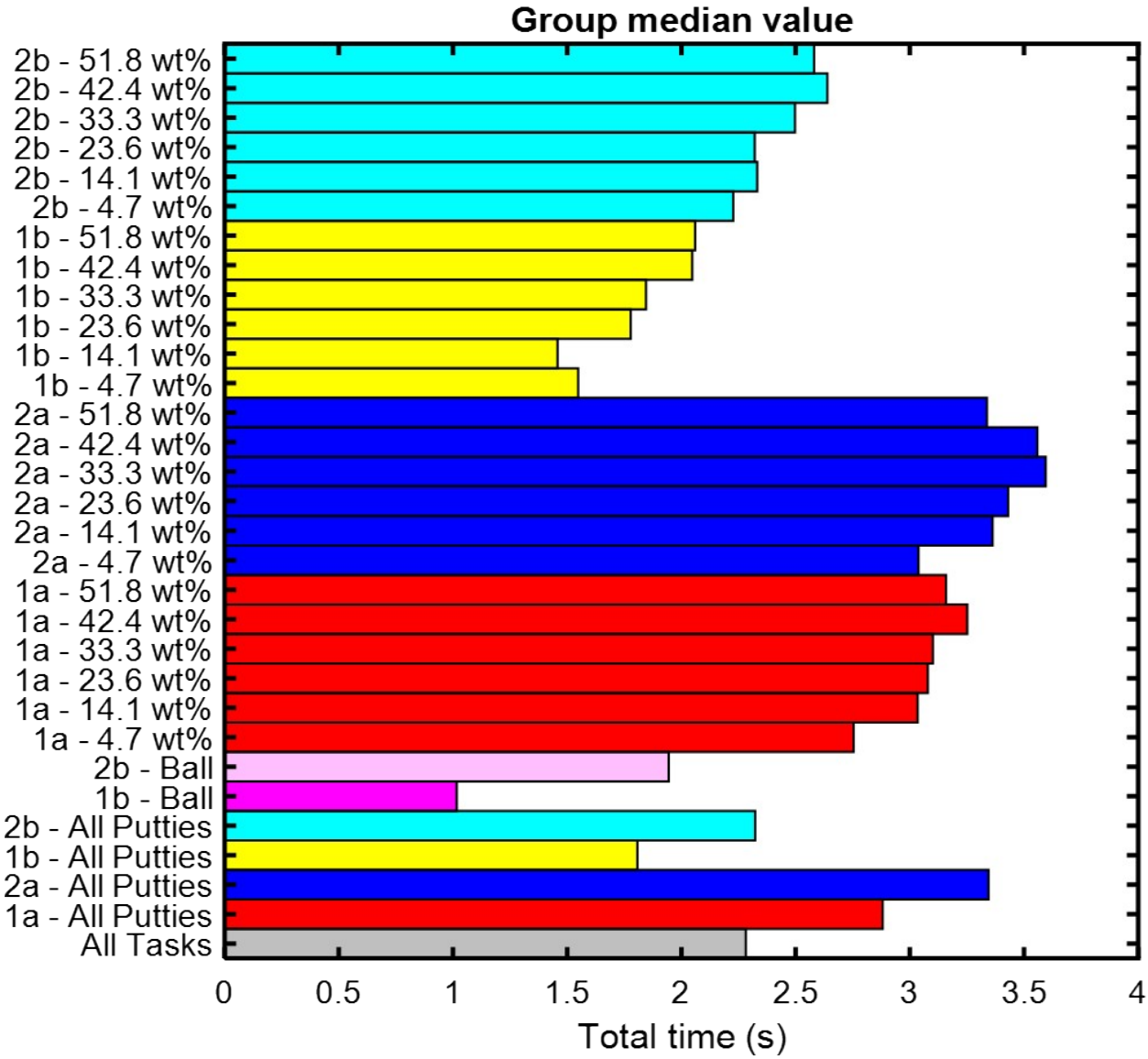
Supplementary Figure 21 – Median recovery time per peak applied by the group in different tasks.



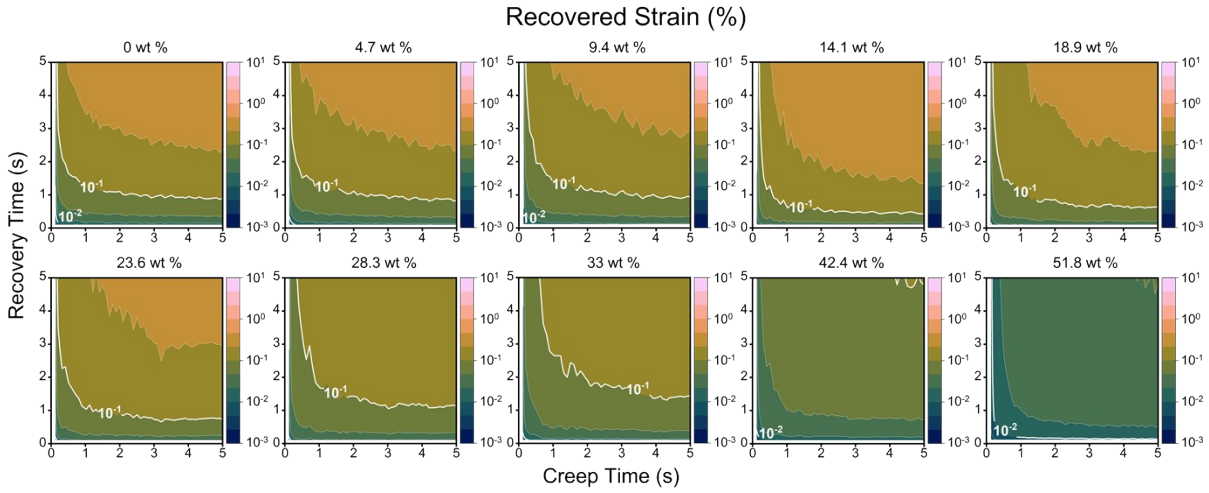
Supplementary Figure 22 – Median total creep time applied by the group in different tasks.



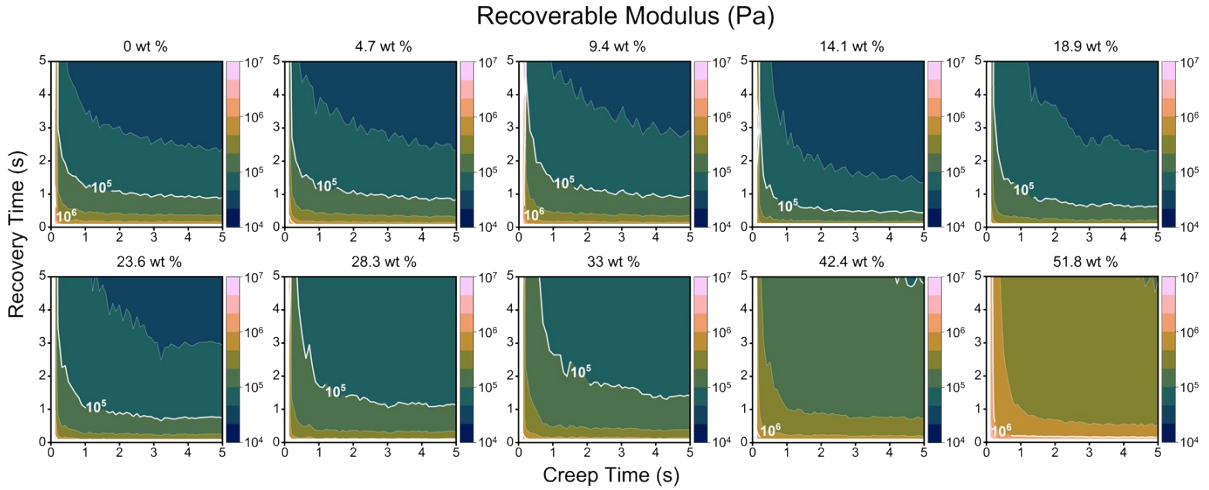
Supplementary Figure 23 – Median total recovery time applied by the group in different tasks.



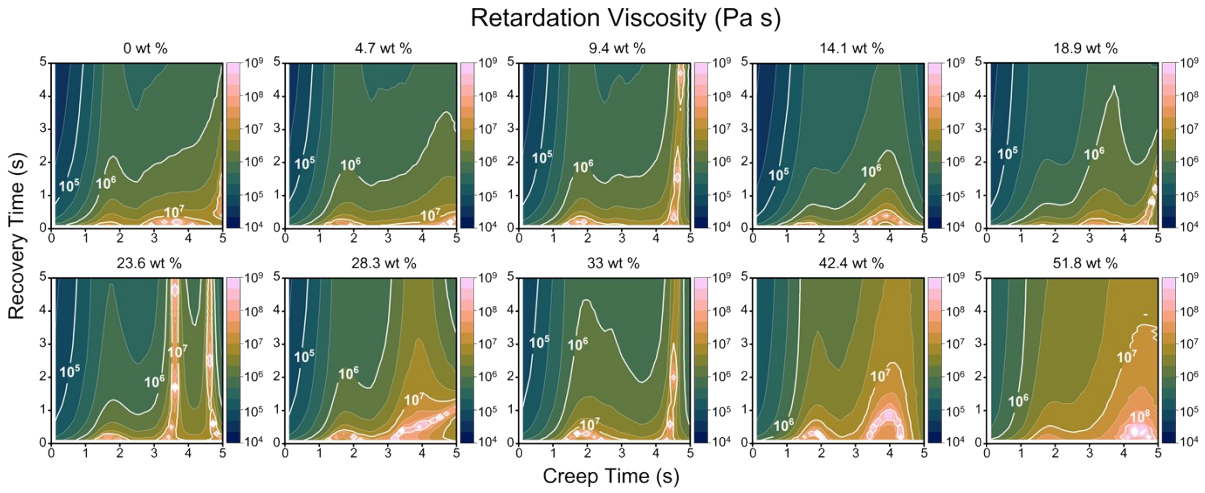
Supplementary Figure 24 – Median total time applied by the group in different tasks.



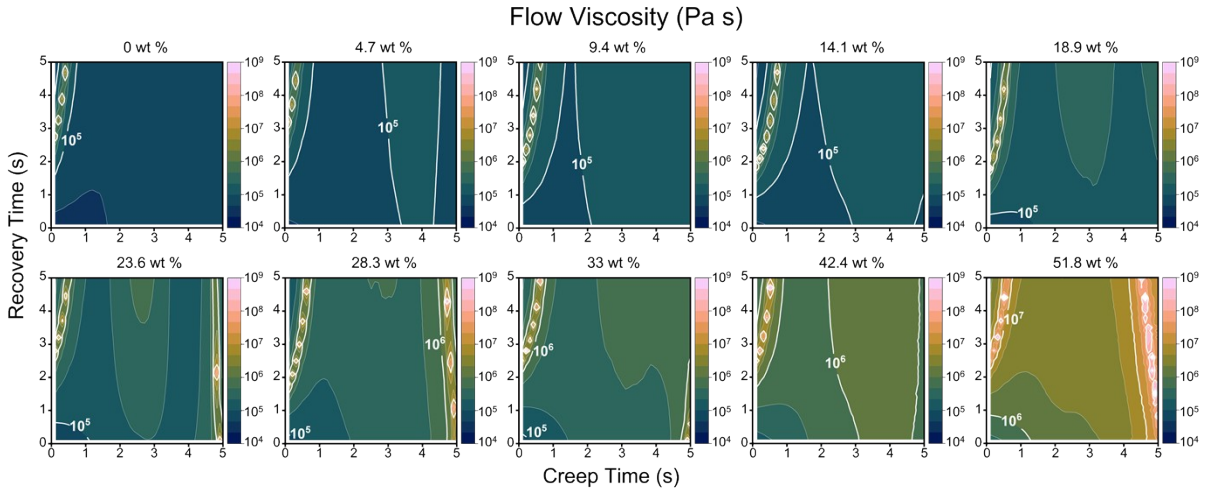
Supplementary Figure 25 – Evolution of the recovered strain at different putty hardener concentrations. The recovered strain is plotted for the first five seconds of creep and recovery following a constant stress of 100 Pa. As the putties become "harder" they experience less strain for an equivalent amount of stress.



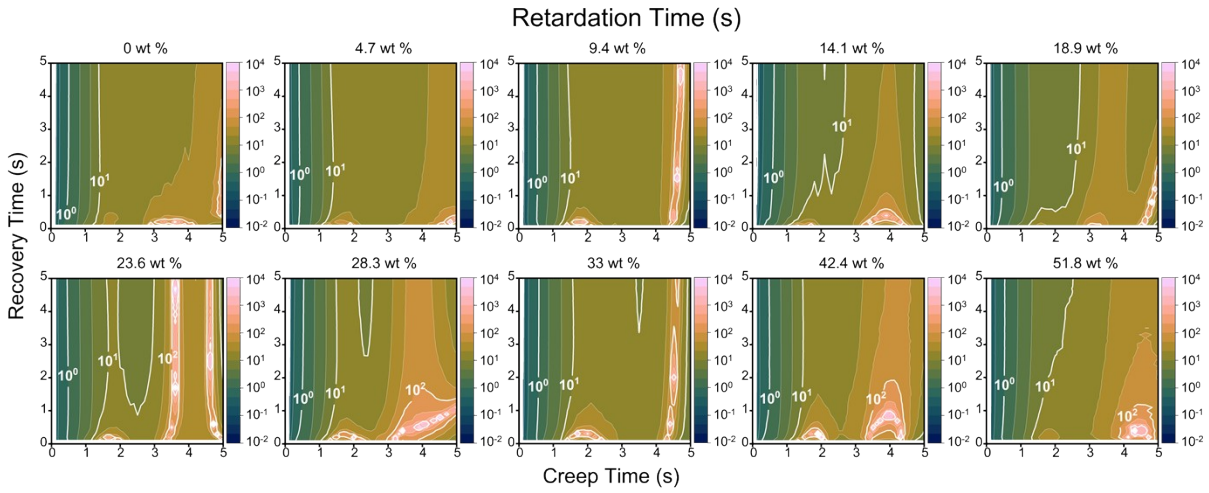
Supplementary Figure 26 – Evolution of the recoverable modulus at different putty hardener concentrations. The recoverable modulus is plotted for the first five seconds of creep and recovery following a constant stress of 100 Pa. As the putties become "harder" the modulus becomes larger.



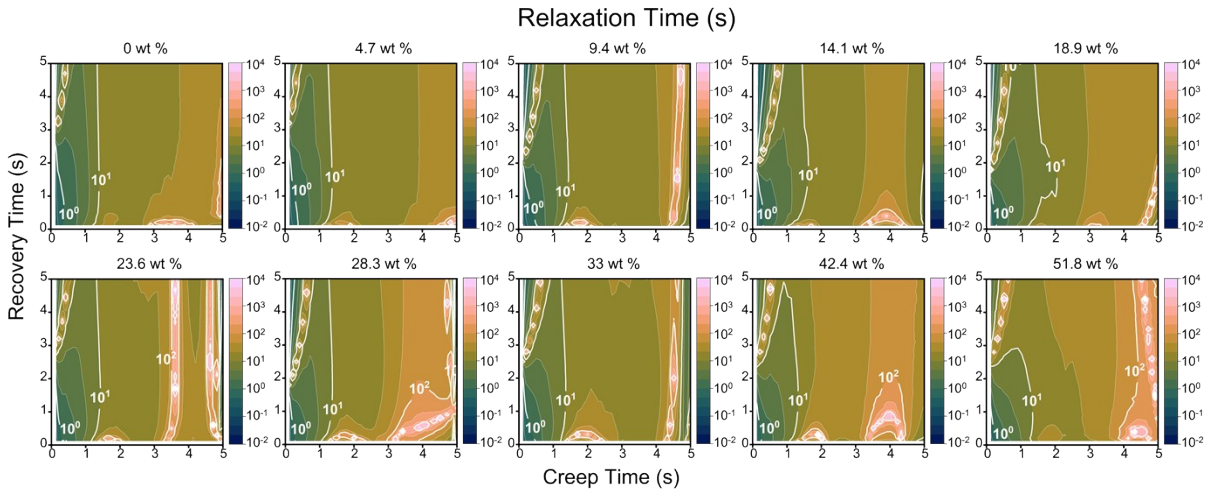
Supplementary Figure 27 – Evolution of the retardation viscosity at different putty hardener concentrations. The retardation viscosity is plotted for the first five seconds of creep and recovery following a constant stress of 100 Pa. As the putties become "harder" the retardation viscosity is largely unchanged, increasing only gradually at the highest concentrations (42.4 and 51.8 wt%).



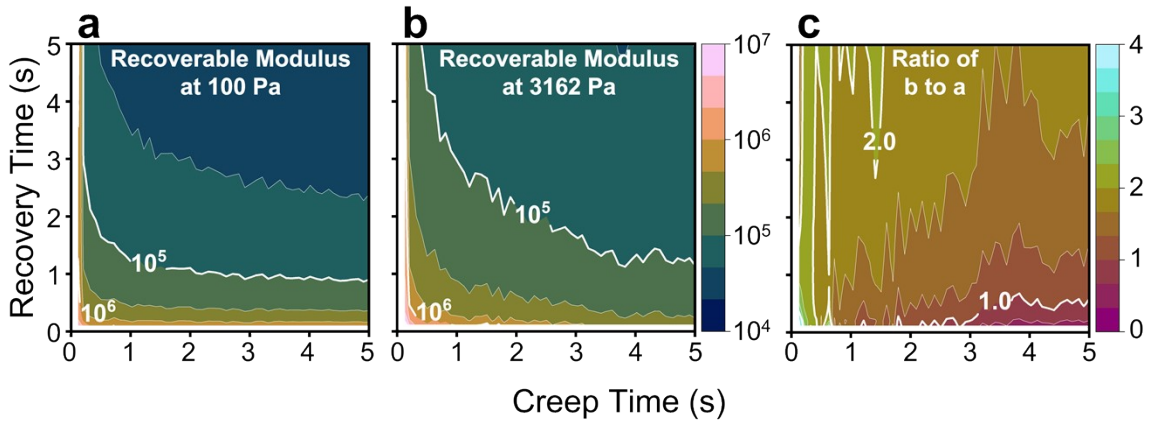
Supplementary Figure 28 – Evolution of the flow viscosity at different putty hardener concentrations. The flow viscosity is plotted for the first five seconds of creep and recovery following a constant stress of 100 Pa. As the putties become "harder" the flow viscosity increases, indicating a greater resistance to flow.



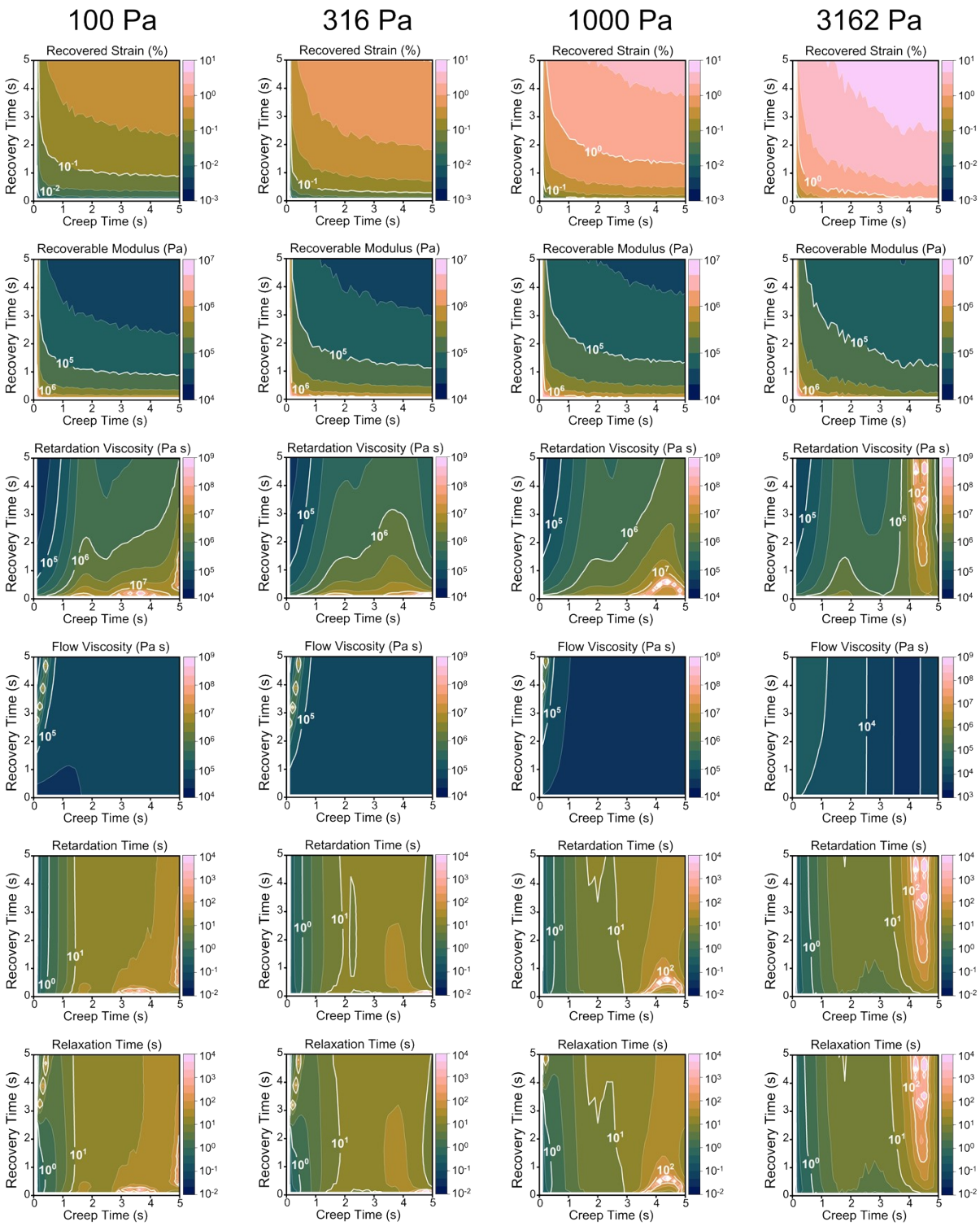
Supplementary Figure 29 – Evolution of the retardation time at different putty hardener concentrations. The retardation time is plotted for the first five seconds of creep and recovery following a constant stress of 100 Pa. As the putties become "harder" the retardation time appears unchanged, indicating the timescales of elastic recovery are the same.



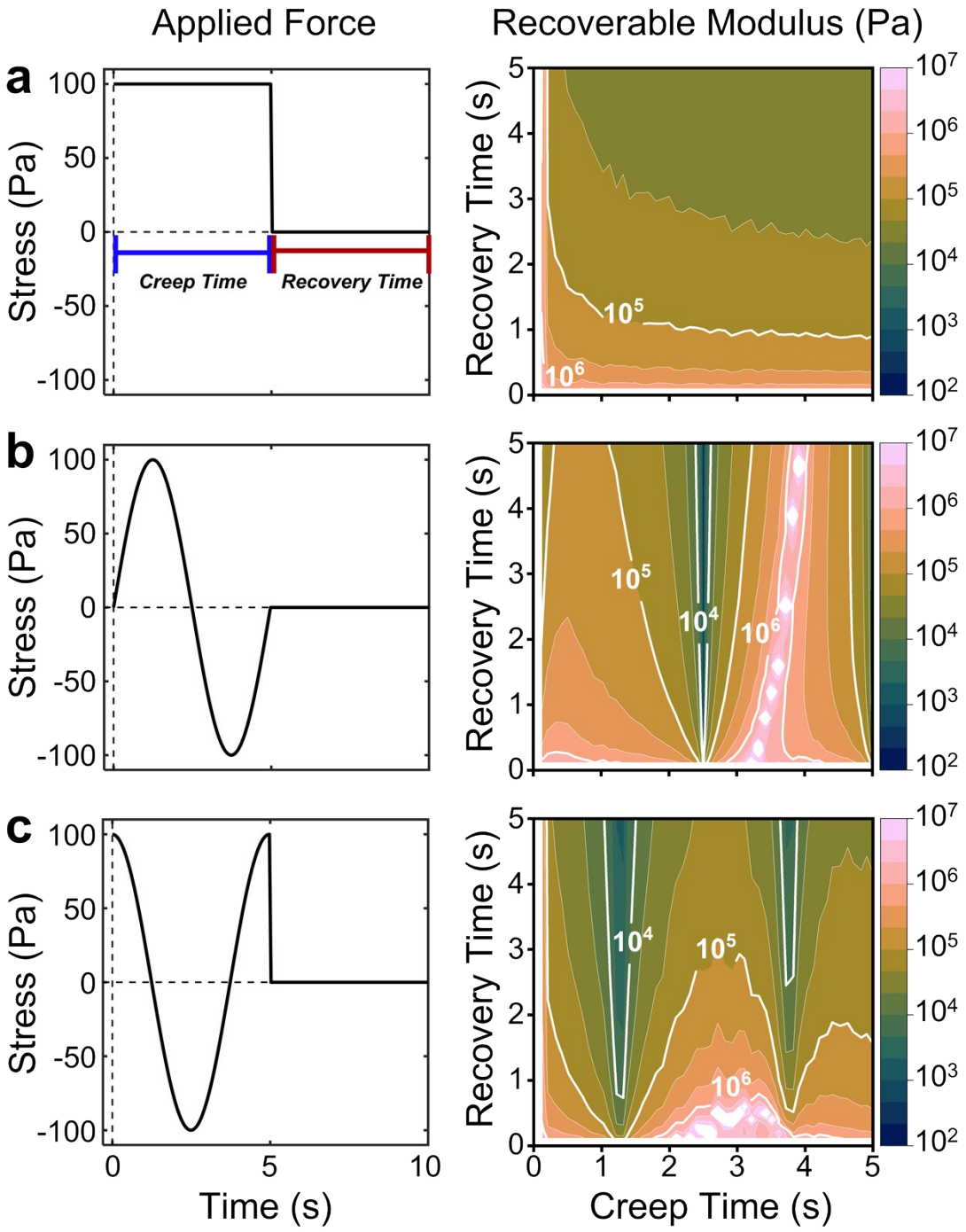
Supplementary Figure 30 – Evolution of the relaxation time at different putty hardener concentrations. The relaxation time is plotted for the first five seconds of creep and recovery following a constant stress of 100 Pa. As the putties become "harder" the relaxation time appears unchanged, indicating the overall timescales of recovery are the same.



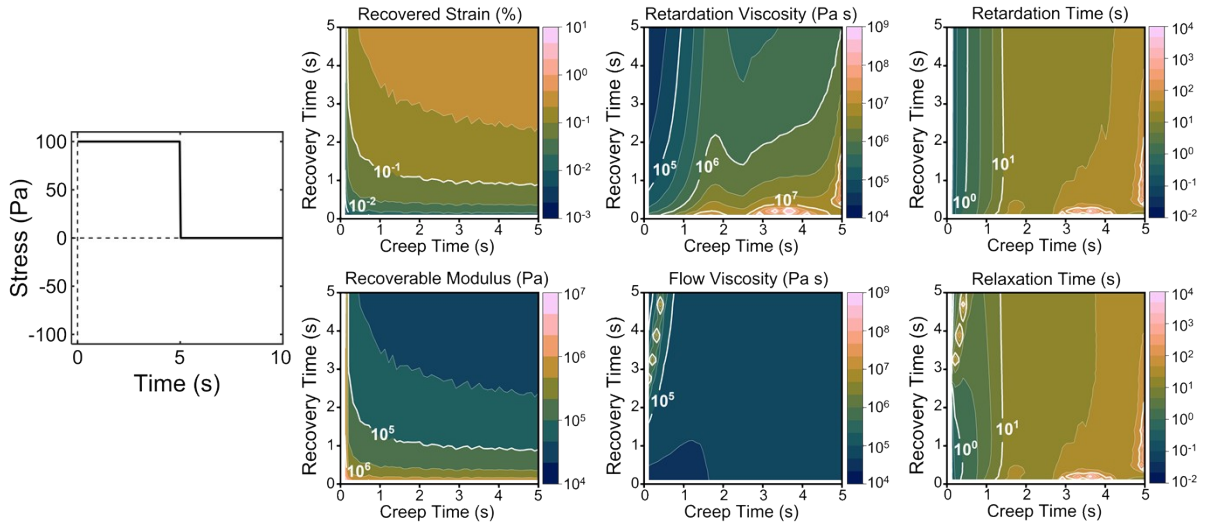
Supplementary Figure 31 – Effects of varying the magnitude of the applied stress on the putties. A constant stress of 100 Pa (a) and 3162 Pa (b) was applied to the putty containing 0 wt% hardener and the evolution of the recoverable modulus is plotted over the first five seconds of creep and recovery. Despite the more than thirtyfold increase in the applied stress, the modulus is largely unchanged. The ratio of plot (b) to plot (a) is shown in (c). The modulus increases by a factor of about 1 to 2.



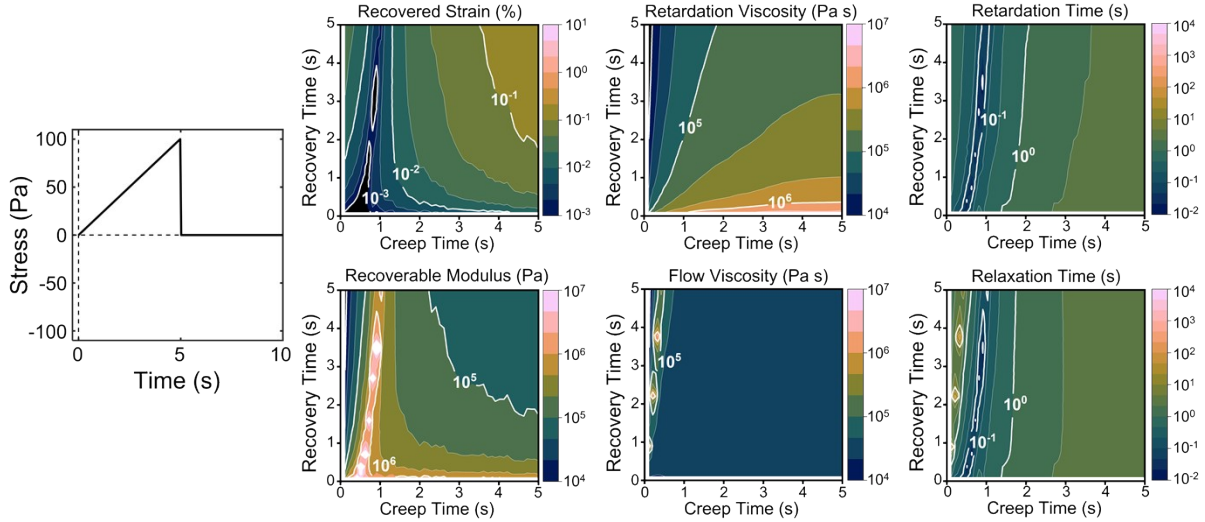
Supplementary Figure 32 – Effects of varying the magnitude of the applied stress on the putties. A more detailed view of Supplementary Figure 32 is shown here. The effects of increasing stress magnitude on all of the recovery rheology terms is shown on the 0 wt% putty following a constant applied stress of 100, 316, 1000, and 3162 Pa for the first five seconds of creep and recovery.



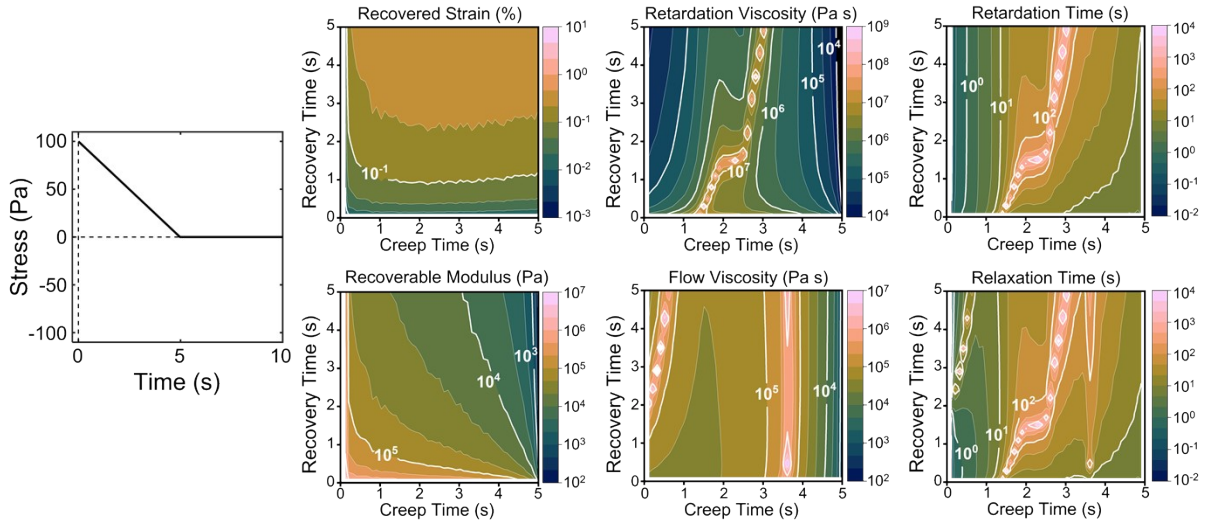
Supplementary Figure 33 – Effects of varying the stress rate applied to the putties. Pictured are the evolution of the recoverable modulus of the putty containing 0 wt% hardener following a constant (a), sinusoidal (b), and cosinusoidal (c) stress protocol. The range of accessible values appears constant, but the location of their value is at different points in time. Therefore, someone can experience different rheology even if they used equivalent amounts of time if they applied different stress rates.



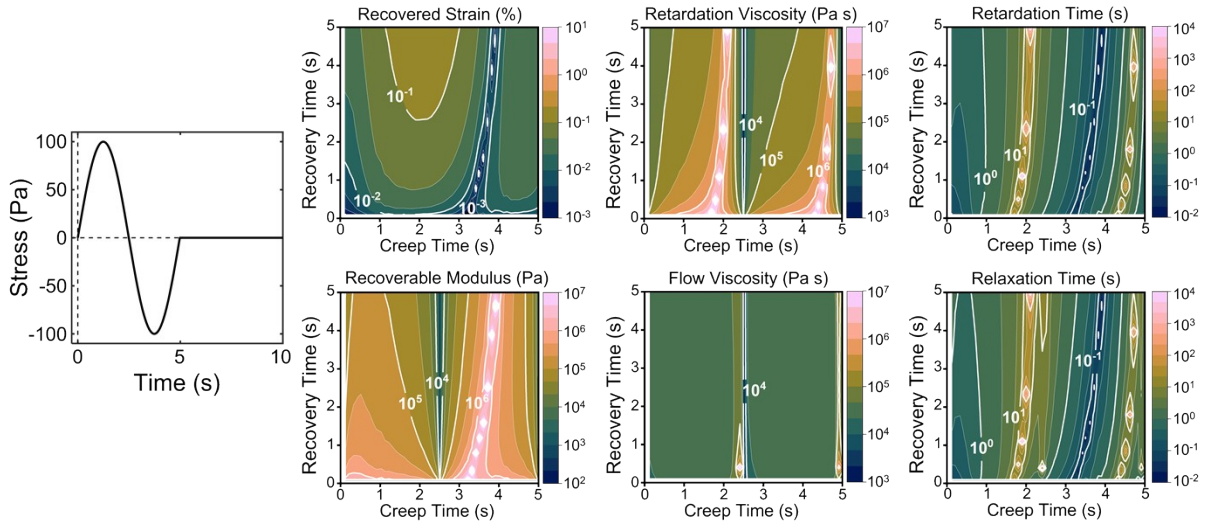
Supplementary Figure 34 – Effects of a zero stress rate. Pictured are the full recovery rheology properties following a constant applied stress (zero stress rate) on a putty containing 0 wt% hardener.



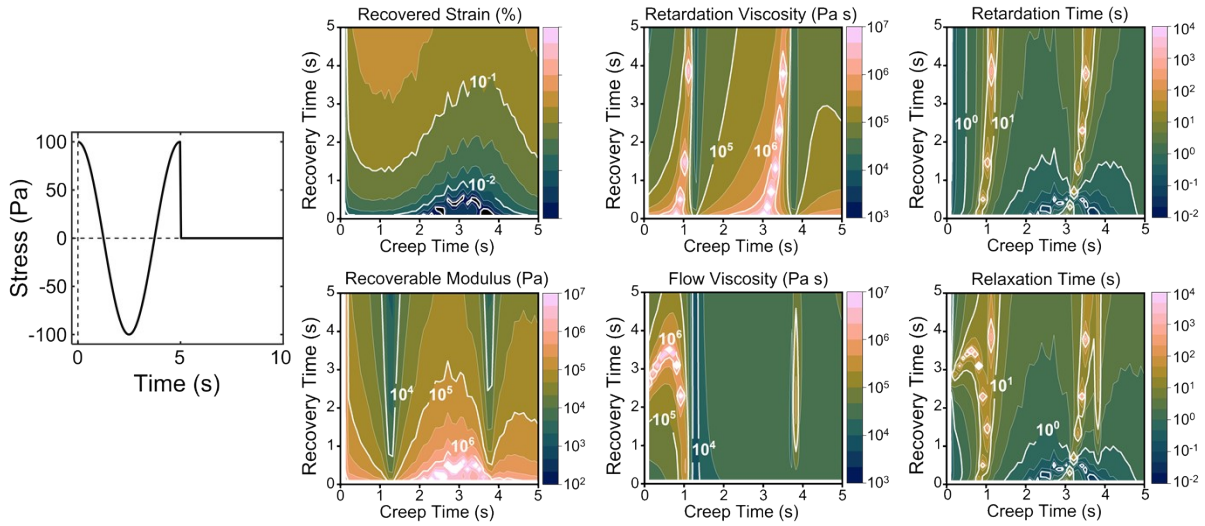
Supplementary Figure 35 – Effects of a constant positive stress rate. Pictured are the full recovery rheology properties following a constant positive stress rate on a putty containing 0 wt% hardener.



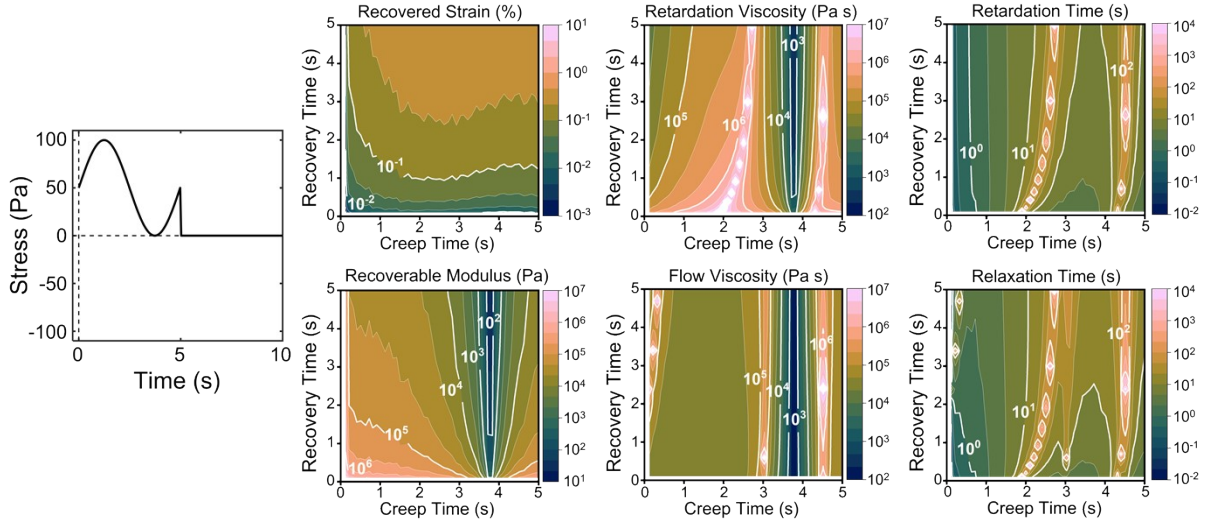
Supplementary Figure 36 – Effects of a constant negative stress rate. Pictured are the full recovery rheology properties following a constant negative stress rate on a putty containing 0 wt% hardener.



Supplementary Figure 37 – Effects of a cosinusoidal stress rate. Pictured are the full recovery rheology properties following a sinusoidal stress wave (cosinusoidal stress rate) on a putty containing 0 wt% hardener.



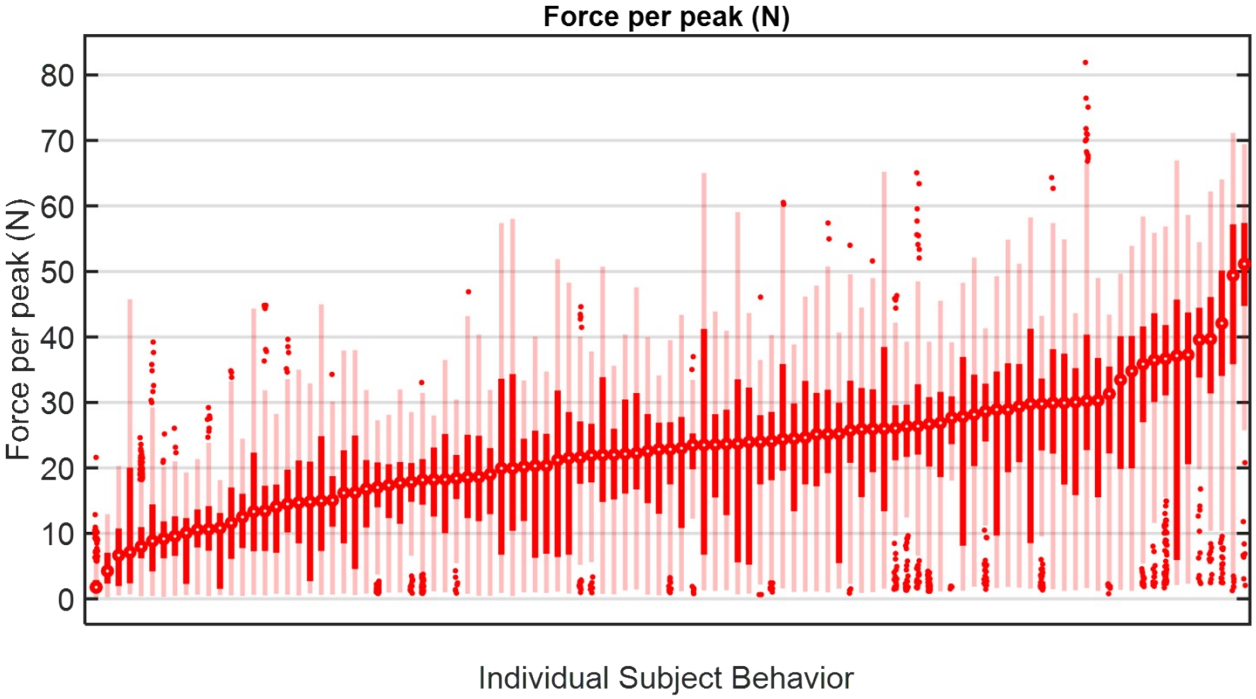
Supplementary Figure 38 – Effects of a sinusoidal stress rate. Pictured are the full recovery rheology properties following a cosinusoidal stress wave (sinusoidal stress rate) on a putty containing 0 wt% hardener.



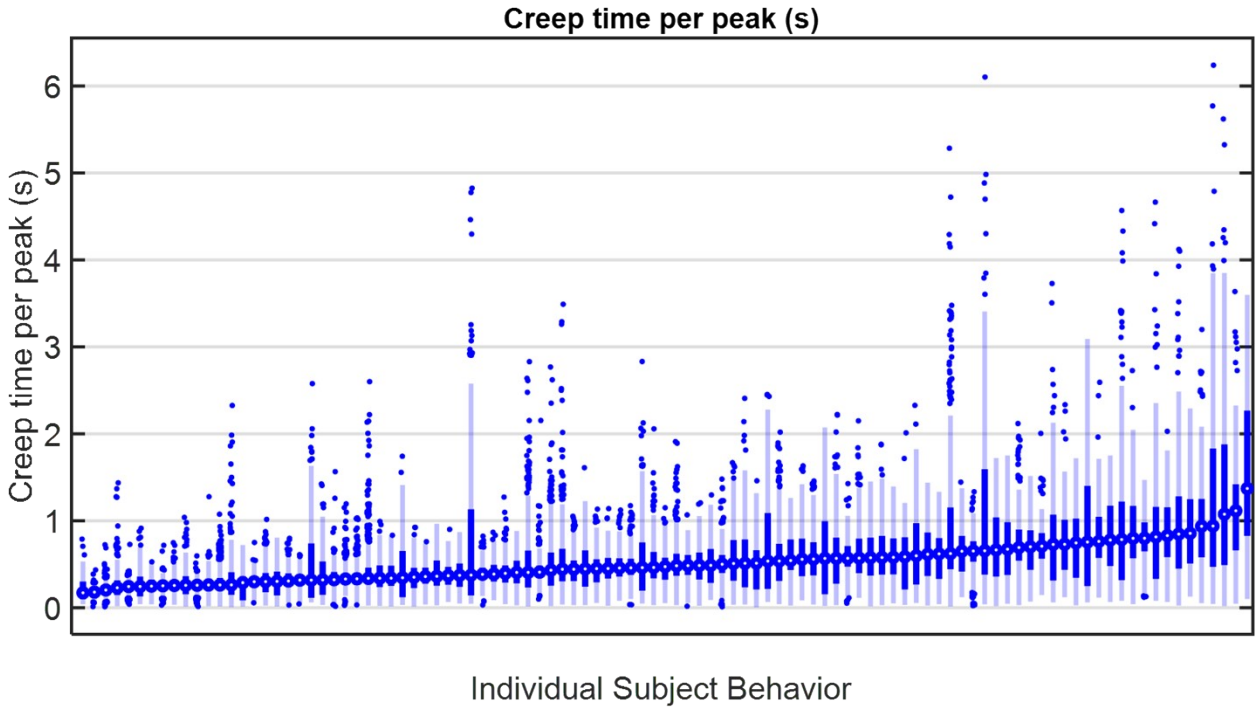
Supplementary Figure 39 – Effects of a cosinusoidal stress rate with always positive stress. Pictured are the full recovery rheology properties following a sinusoidal stress wave (cosinusoidal stress rate) on a putty containing 0 wt% hardener where the applied stress is never negative.

Boxplots of Overall User Behavior

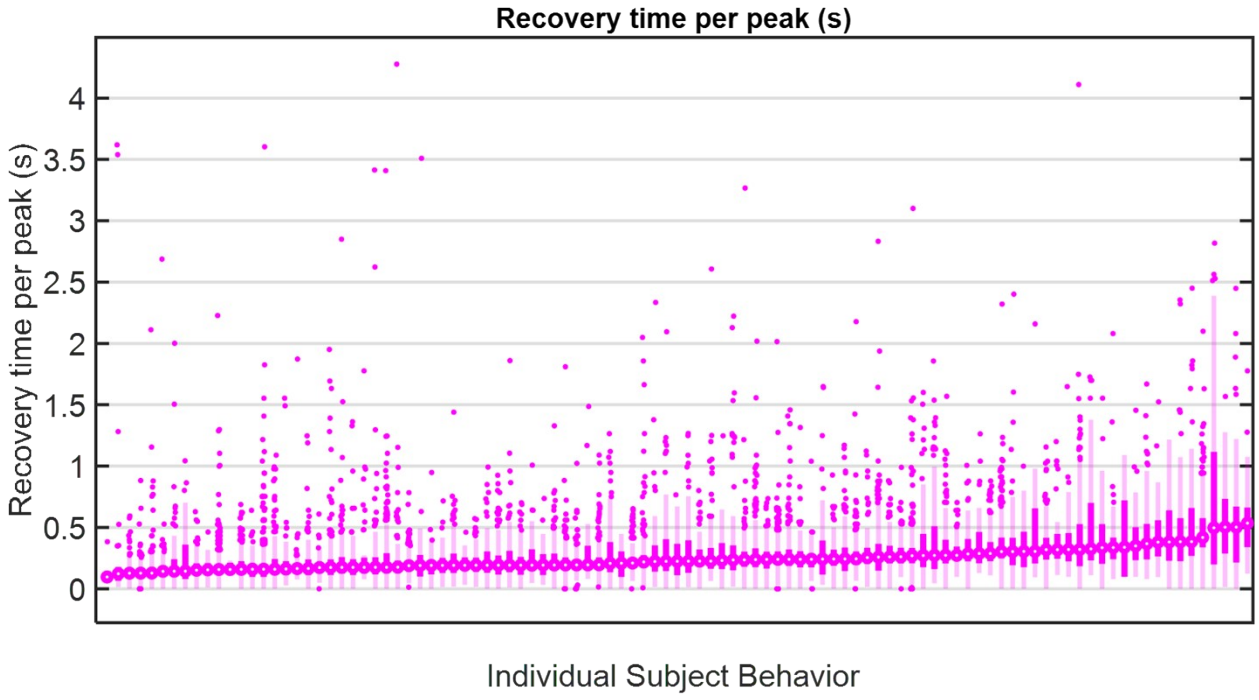
It is difficult to report the subtleties of every interaction a user has with a material. Simplifications, such as using the mean or median of a dataset, are convenient, but they erase underlying nuances that appear in the material's physical responses. To reinforce the idea that considering only a single value of any behavior is ill-advised, Supplementary Figures 41 – 54 show boxplots demonstrating the range of behaviors exhibited by both the individual and the group. Data presented in Supplementary Figures 41 – 54 include all sensory data evaluated in Tasks 1a, 1b, 2a, and 2b. Subjects are arranged by increasing median value, and an individual's relative placement across the abscissa is not necessarily the same for each figure.



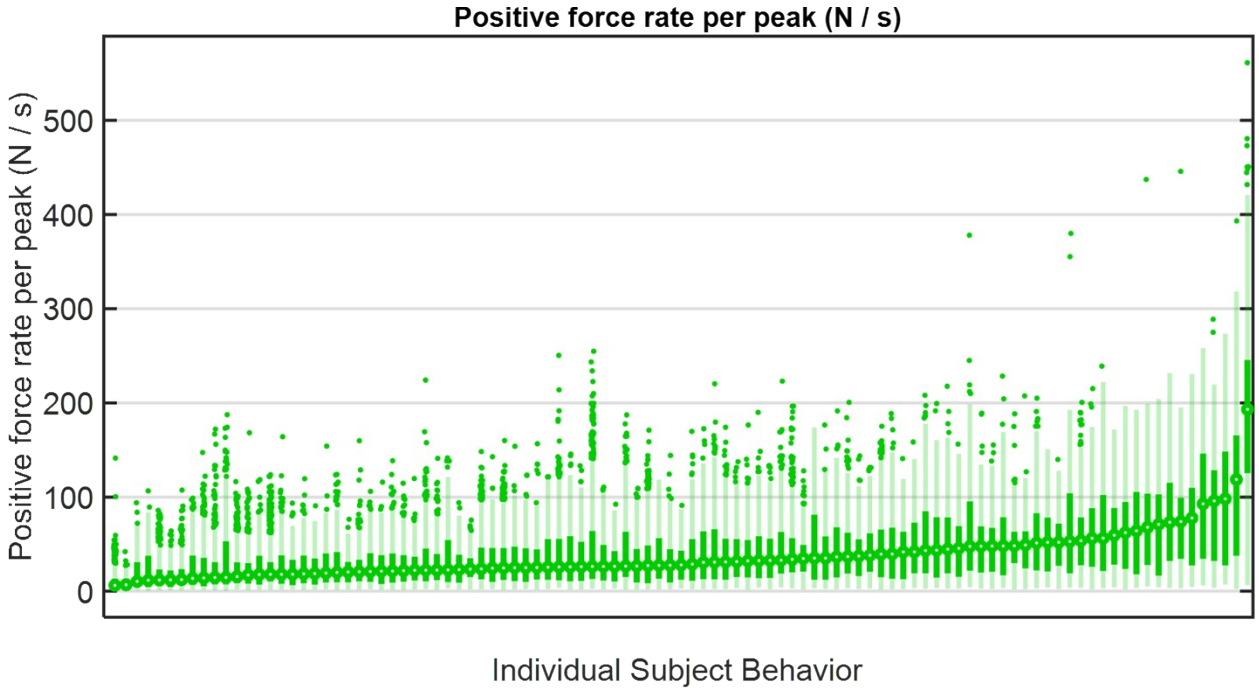
Supplementary Figure 40 – Boxplots showing the force per peak applied by each subject. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



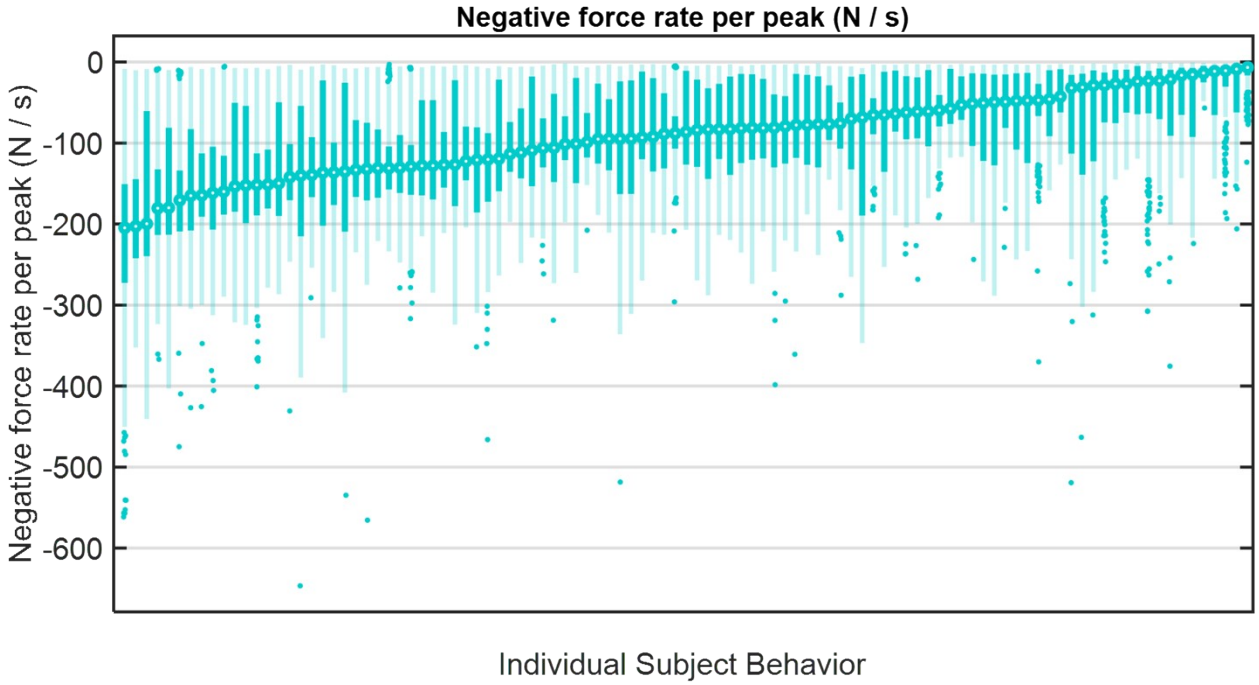
Supplementary Figure 41 – Boxplots showing the creep time per peak applied by each subject. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



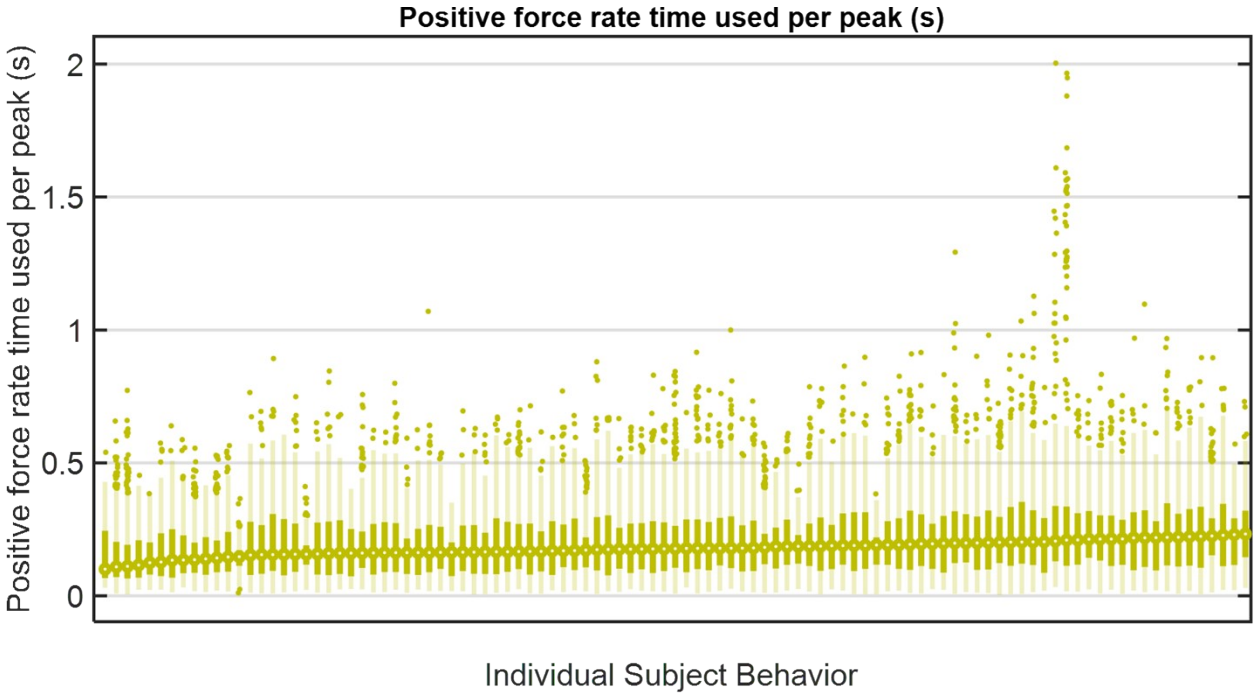
Supplementary Figure 42 – Boxplots showing the recovery time per peak applied by each subject. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



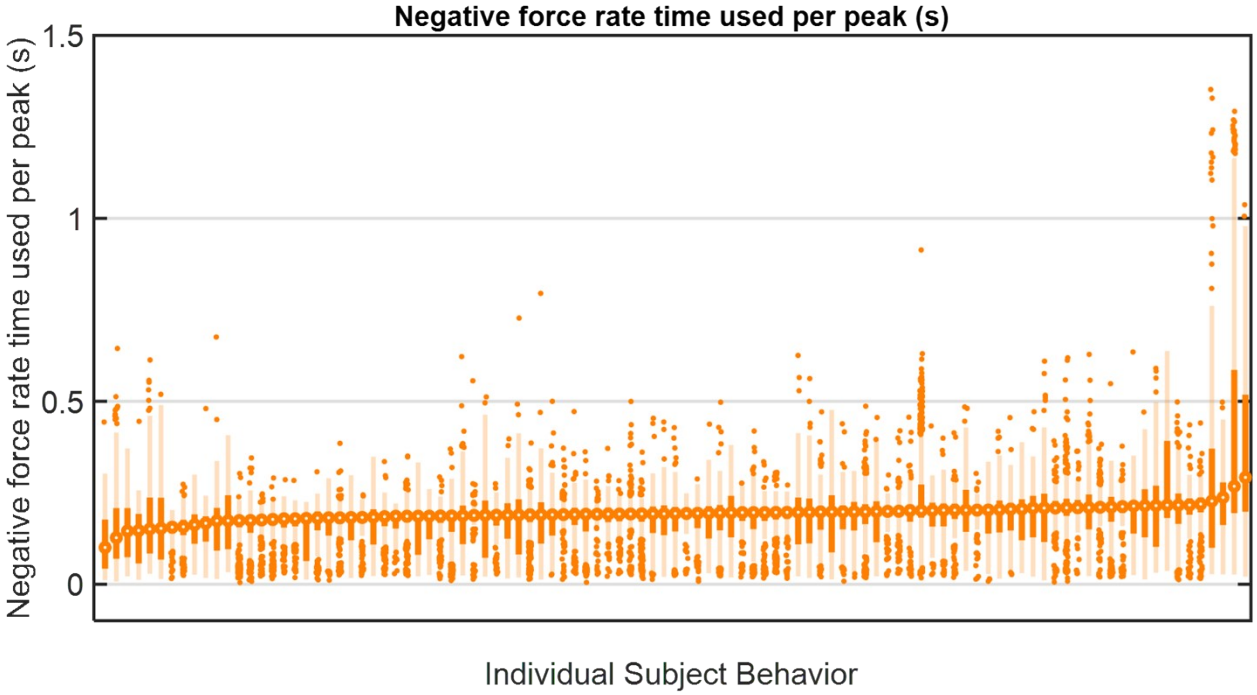
Supplementary Figure 43 – Boxplots showing the positive force rate per peak applied by each subject. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



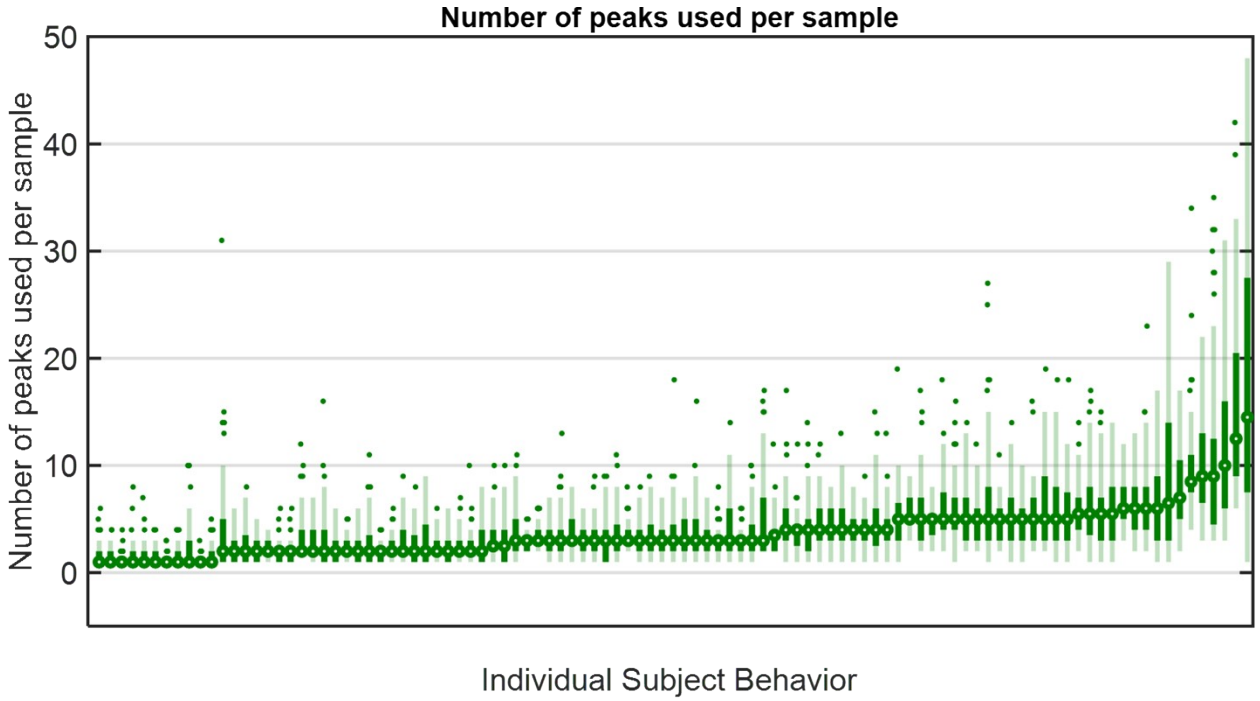
Supplementary Figure 44 – Boxplots showing the negative force rate per peak applied by each subject. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



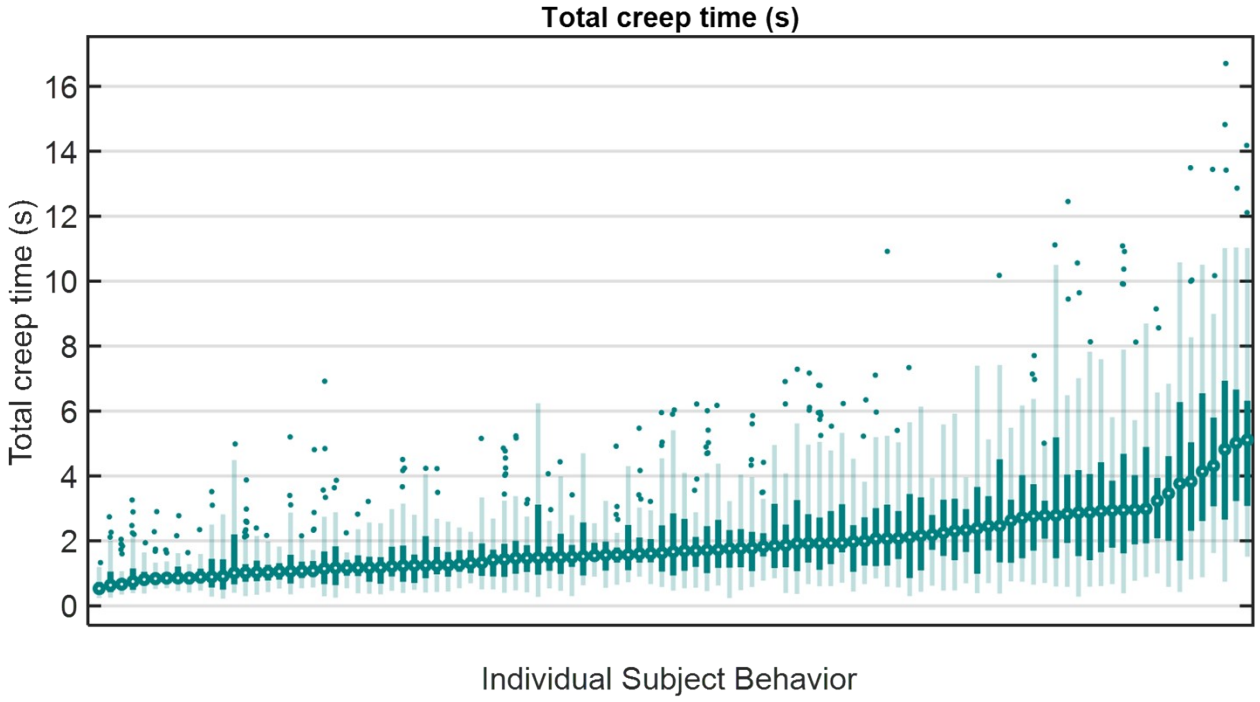
Supplementary Figure 45 – Boxplots showing the time used for a positive force rate peak applied by each subject. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



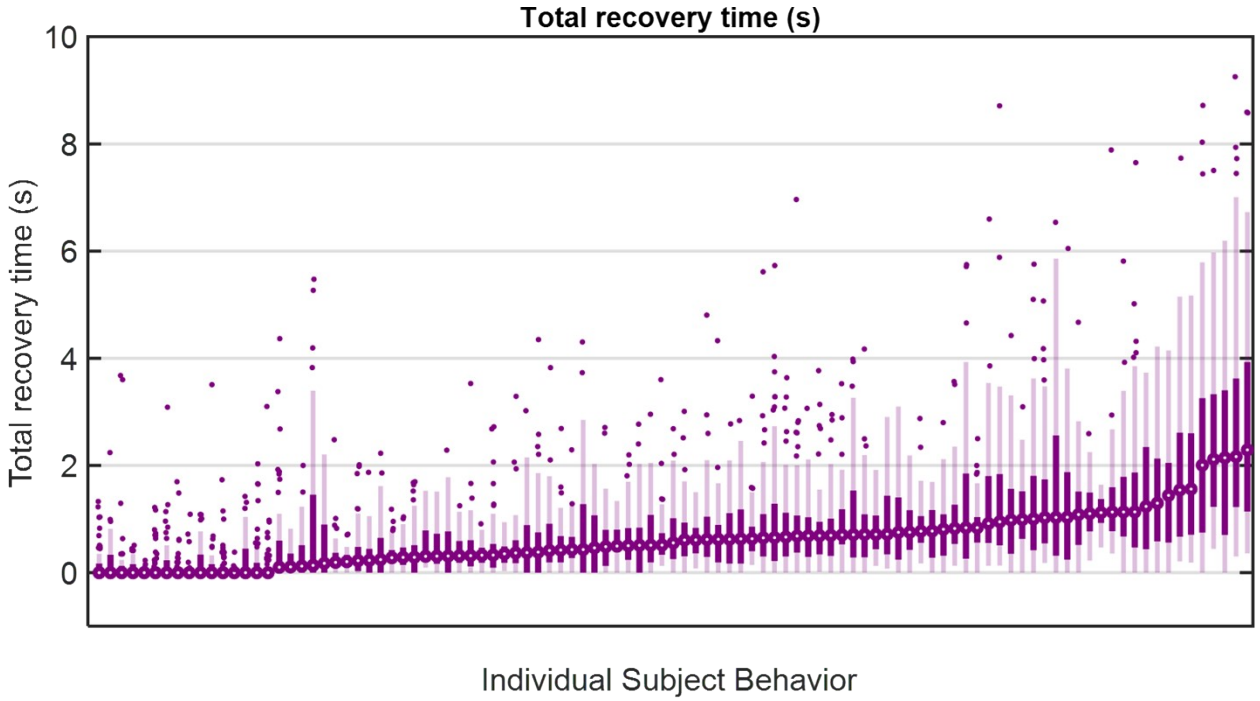
Supplementary Figure 46 – Boxplots showing the time used for a negative force rate peak applied by each subject. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



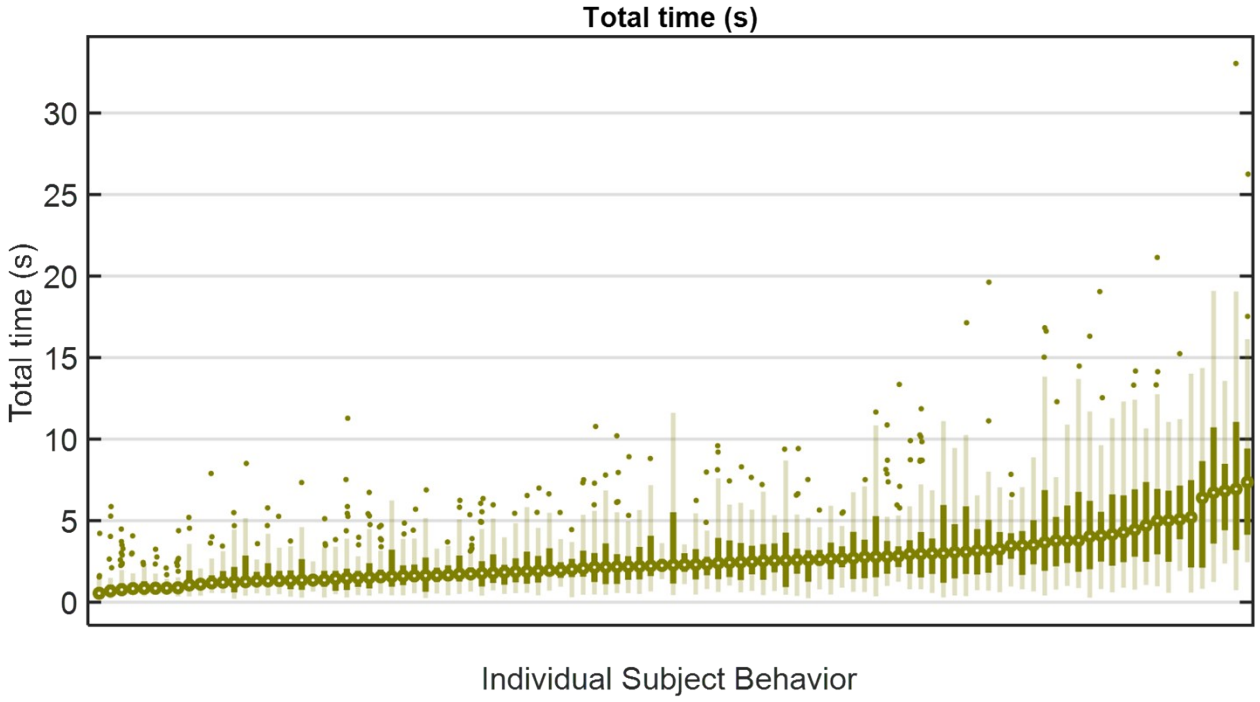
Supplementary Figure 47 – Boxplots showing the number of peaks applied by each subject when examining a particular sample. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



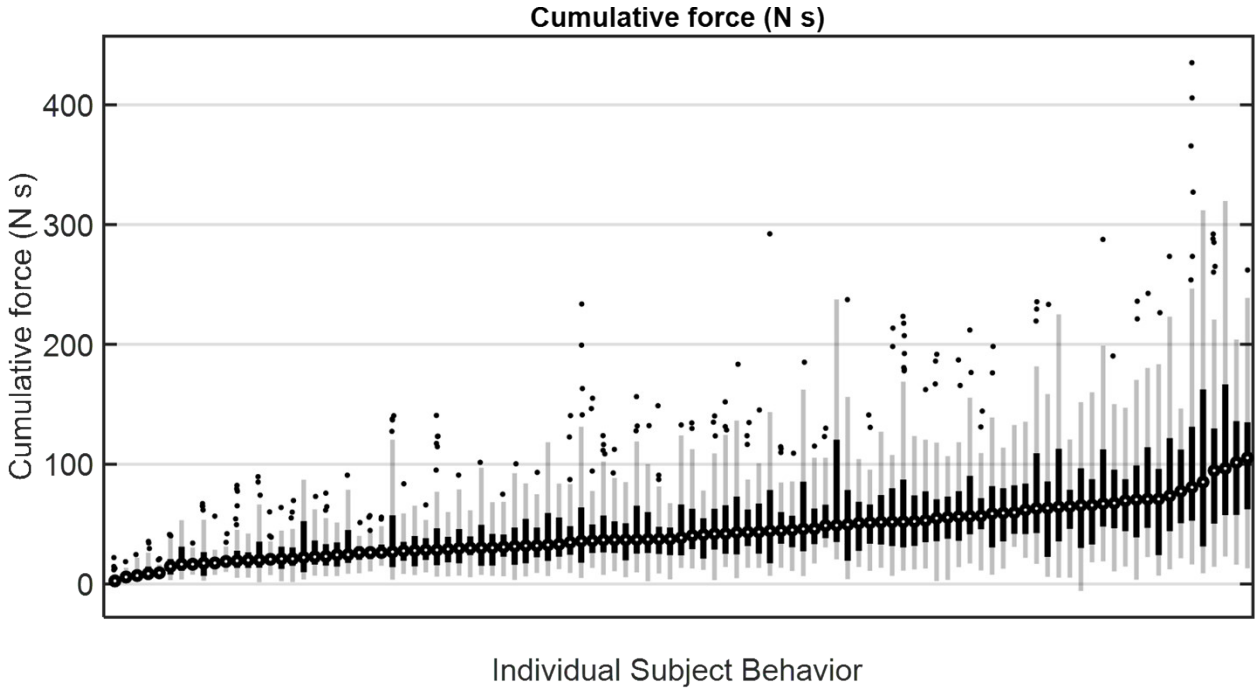
Supplementary Figure 48 – Boxplots showing the total creep time applied by each subject when examining a particular sample. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



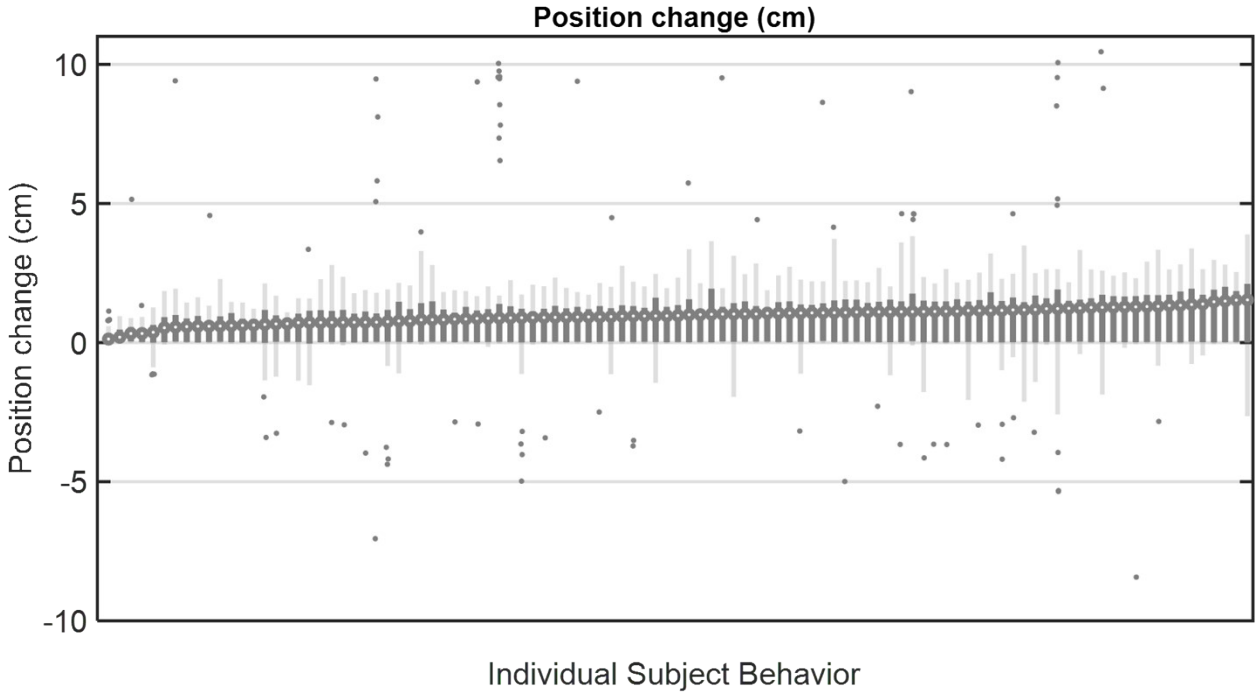
Supplementary Figure 49 – Boxplots showing the total recovery time applied by each subject when examining a particular sample. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



Supplementary Figure 50 – Boxplots showing the total time applied by each subject when examining a particular sample. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.

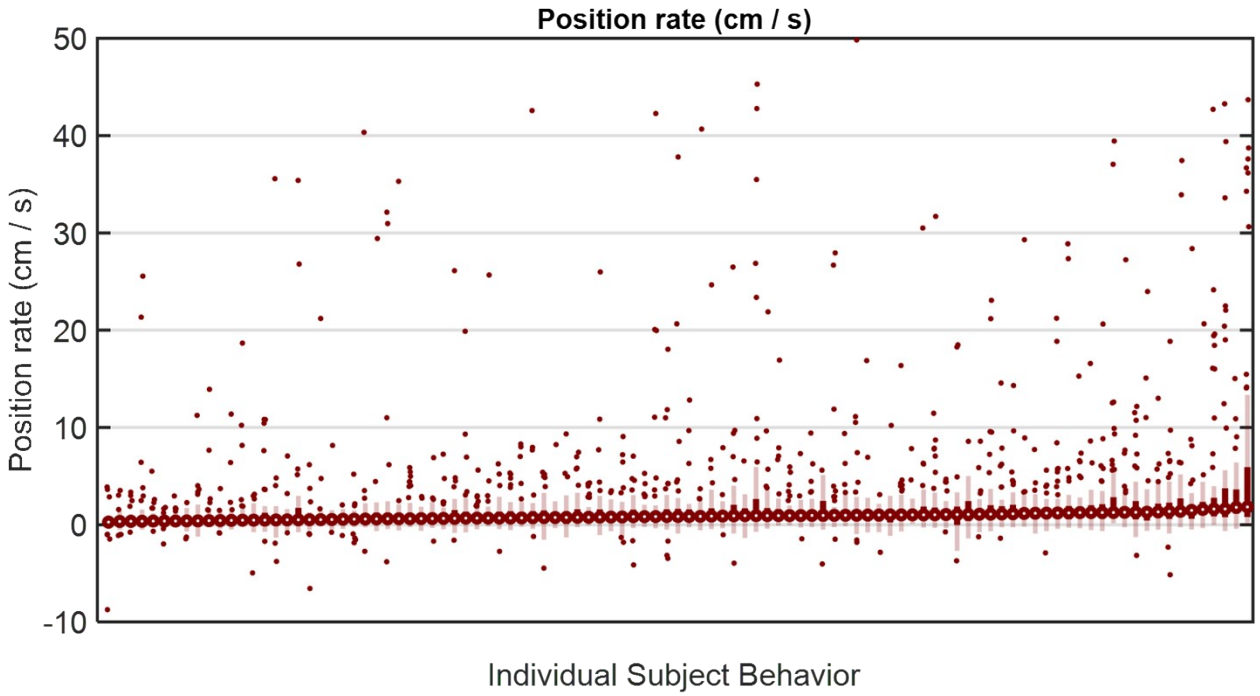


Supplementary Figure 51 – Boxplots showing the cumulative force applied by each subject when examining a particular sample. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b.



Supplementary Figure 52 – Boxplots showing the total change in position applied by each subject when examining a particular sample. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b. Note that

measures of position change are inherently noisier than the force data since the rely on optical distance measurement from a sensor placed above the sample. Events such as the finger interfering with the beam or shifting of the sample can lead to noise (such as negative values).



Supplementary Figure 53 – Boxplots showing the total change in position applied by each subject when examining a particular sample. The boxplots show the median (central white dot), interquartile range (solid colored bar), whiskers (light colored bar), and outliers (small colored dots). Data includes analysis of sensory data from Tasks 1a, 1b, 2a, and 2b. Note that measures of position change are inherently noisier than the force data since the rely on optical distance measurement from a sensor placed above the sample. Events such as the finger interfering with the beam or shifting of the sample can lead to noise (such as negative values).