

Pre/post measurements

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Analysis of longitudinal data

Advantages

- More power than cross sectional studies
- Each subject is its own control person
- Information about individual changes

Challenges

- Missing values
- Predictors can change over time
- In cross over designs: carry over effects

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Today we will consider the simplest case with only two time points: pre and post score

Outline

- ① *t* test
- ② Change score analysis
- ③ Analysis of Covariance
- ④ Example: Acupuncture for shoulder pain
- ⑤ Linear mixed-effects model

1 t test

t test for dependent samples (comparing two time points)

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$$y_{i2} = \beta_0 + y_{i1} + \varepsilon_i$$

with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

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- Which effects are not considered by this?

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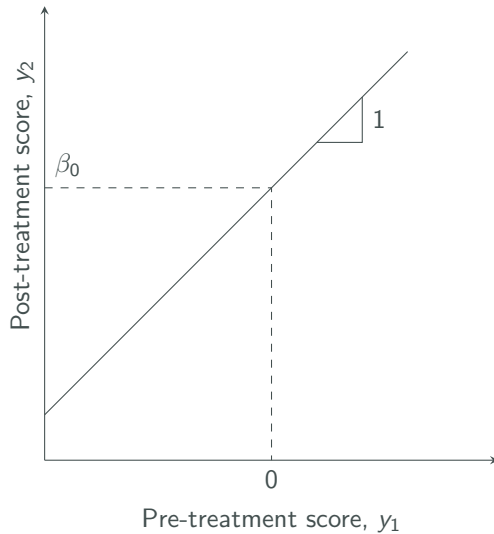
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- Interpretation:

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- Hypothesis:
Is there change between the first and second time point ($H_0: \beta_0 = 0$)?
- Which effects are not considered by this?
- It is unclear if change is due to the treatment or just appeared over time

t test for comparing two time points



t test for comparing two time points

```
# simulate two dependent time points
cg <- MASS::mvrnorm(n = 50, mu = c(10, 10),
                    Sigma = matrix(c(1, .9, .9, 1), nrow = 2))
tg <- MASS::mvrnorm(n = 50, mu = c(10, 15),
                    Sigma = matrix(c(1, .9, .9, 1), nrow = 2))

sim <- as.data.frame(rbind(cg, tg))
names(sim) <- c("t1", "t2")

# add group variable
sim$group <- factor(rep(c("CG", "TG"), each = 50))

# group means
aggregate(cbind(t1, t2) ~ group, data = sim, FUN = mean)
```

t test for comparing two time points

```
# t test
t.test(sim$t2, sim$t1, paired = TRUE)

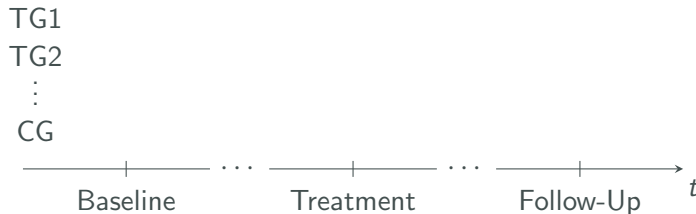
# add change score
sim$d <- sim$t2 - sim$t1

# linear model
lm1 <- lm(d ~ 1, data = sim)
lm2 <- lm(t2 ~ offset(t1), data = sim)

# visualization
plot(t2 ~ t1, data = sim)
abline(coef(lm2), 1)
```

Better design

- At least two groups are observed before (y_{i1}) and after (y_{i2}) a treatment



- Research question:
Do groups differ in the strength of their change?

t test of follow-up score of two groups

- In regression notation with $x_i = 1$, if i th person is part of the treatment group, and else 0:

$$y_{i2} = \beta_0 + \beta_1 x_i + \varepsilon_i$$

with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

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- Interpretation:

β_0	average follow-up score of reference group
β_1	effect of treatment group

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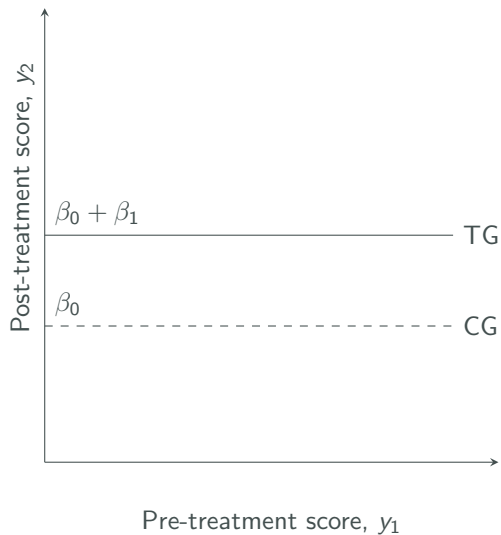
with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

- Interpretation:

β_0 average follow-up score of reference group
 β_1 effect of treatment group

- Hypothesis:
Do groups differ at the second time point ($H_0: \beta_1 = 0$)?
- Since the baseline score is not considered, estimate of the change is biased

t test of follow-up score of two groups



t test of follow-up score of two groups

```
# t test
t.test(t2 ~ group, data = sim, var.equal = TRUE)

# linear model
lm3 <- lm(t2 ~ group, data = sim)

# visualization
plot(t2 ~ t1, sim)
abline(h = cumsum(coef(lm3)))
```

② Change score analysis

Change score analysis

- Regression model

$$d_i = \beta_0 + \beta_1 x_i + \varepsilon_i$$

$$y_{i2} - y_{i1} = \beta_0 + \beta_1 x_i + \varepsilon_i$$

$$y_{i2} = \beta_0 + y_{i1} + \beta_1 x_i + \varepsilon_i$$

with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

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with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

- Interpretation:
 - β_0 average change score for reference group
 - β_1 difference to β_0 in treatment group

Change score analysis

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 - Is there change in the reference group ($H_0: \beta_0 = 0$)?

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with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

- Interpretation:

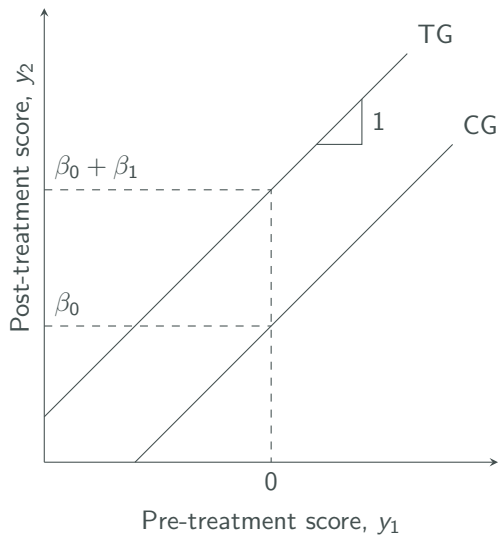
β_0 average change score for reference group

β_1 difference to β_0 in treatment group

- Hypotheses:

- Is there change in the reference group ($H_0: \beta_0 = 0$)?
- Does the change differ between groups ($H_0: \beta_1 = 0$)?

Change score analysis



Change score analysis

```
# regression model
lm4 <- lm(t2 ~ offset(t1) + group, data = sim)

# visualization
plot(t2 ~ t1, data = sim)
abline(coef(lm4)[1], 1)
abline(coef(lm4)[1] + coef(lm4)[2], 1)
```

Regression to the mean

- Change score analysis is based on the often too restrictive assumption that the follow-up score depends on the baseline score with a slope of 1
- Often baseline scores are negatively correlated with the change scores: Persons with low (bad) scores improve more than persons with high scores
- This regression to the mean lets us expect a slope of < 1 which has to be estimated from the data

③ Analysis of Covariance

Analysis of Covariance (ANCOVA)

- Regression model

$$y_{i2} = \beta_0 + \beta_1 y_{i1} + \beta_2 x_i + \varepsilon_i$$

with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

Analysis of Covariance (ANCOVA)

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$$y_{i2} = \beta_0 + \beta_1 y_{i1} + \beta_2 x_i + \varepsilon_i$$

with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

- Interpretation:

β_0 average follow-up score in the reference group for $y_{i1} = 0$
 β_1 effect of baseline score
 β_2 difference to follow-up score in the treatment group

Analysis of Covariance (ANCOVA)

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- Hypotheses:

- Is there a relationship between baseline and follow-up score ($H_0: \beta_1 = 0$)?

Analysis of Covariance (ANCOVA)

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β_0 average follow-up score in the reference group for $y_{i1} = 0$

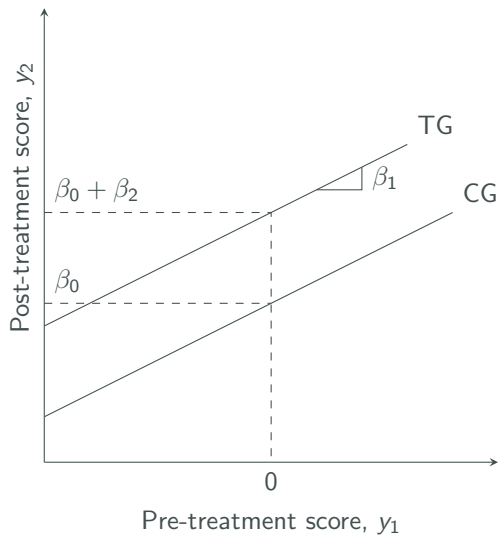
β_1 effect of baseline score

β_2 difference to follow-up score in the treatment group

- Hypotheses:

- Is there a relationship between baseline and follow-up score ($H_0: \beta_1 = 0$)?
- Do the follow-up scores in the groups differ for persons with identical baseline scores ($H_0: \beta_2 = 0$)?

Analysis of Covariance (ANCOVA)



Adjusted means

- With an ANCOVA model we can predict average follow-up scores for persons with the same baseline score
- For example, we get

$$\hat{y}_{i2} = \hat{\beta}_0 + \hat{\beta}_1 \bar{y}_1 + \hat{\beta}_2 x_i$$

for an average baseline score \bar{y}_1

- These conditional means are sometimes called (baseline) adjusted means

Analysis of Covariance (ANCOVA)

```
# ancova
lm5 <- lm(t2 ~ t1 + group, data = sim)

# adjusted means
predict(lm5, newdata = data.frame(t1 = mean(sim$t1),
                                   group = c("CG", "TG")))

# ancova with change score
lm5a <- lm(d ~ t1 + group, data = sim)

# visualization
plot(t2 ~ t1, data = sim)
abline(coef(lm5)[1], coef(lm5)[2])
abline(coef(lm5)[1] + coef(lm5)[3], coef(lm5)[2])
```

Analysis of Covariance with change score

- Regression model

$$d_i = \beta_0 + \beta_1 y_{i1} + \beta_2 x_i + \varepsilon_i$$

$$y_{i2} - y_{i1} = \beta_0 + \beta_1 y_{i1} + \beta_2 x_i + \varepsilon_i$$

$$y_{i2} = \beta_0 + (1 + \beta_1) y_{i1} + \beta_2 x_i + \varepsilon_i$$

- For testing the difference of change in the groups (β_2) it is irrelevant if the dependent variable is the follow-up score or the change score

Different slopes for groups

- Regression model

$$y_{i2} = \beta_0 + \beta_1 y_{i1} + \beta_2 x_i + \beta_3 (y_{i1} \cdot x_i) + \varepsilon_i$$

with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

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with $\varepsilon_i \sim N(0, \sigma^2)$ i.i.d.

- Interpretation:

β_0 average follow-up score in reference group for $y_{i1} = 0$
 β_1 effect of baseline score
 β_2 difference to follow-up score in treatment group
 β_3 difference between slopes in reference and treatment groups

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- Hypothesis:

Does effect of baseline score depend on group ($H_0: \beta_3 = 0$)?

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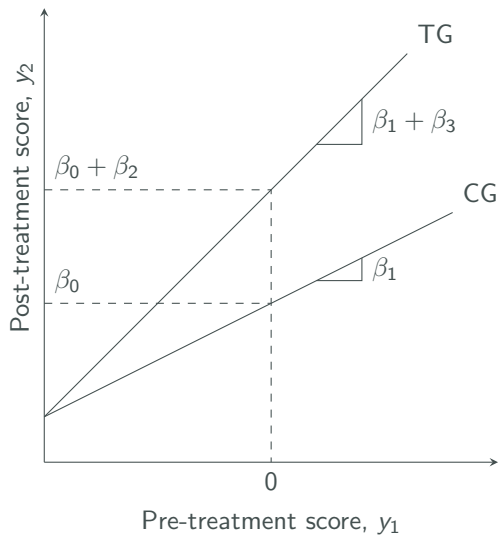
β_3 difference between slopes in reference and treatment groups

- Hypothesis:

Does effect of baseline score depend on group ($H_0: \beta_3 = 0$)?

- Interpretation of adjusted means independently of baseline score implies $\beta_3 = 0$

Interaction between baseline score and group



Interaction between baseline score and group

```
# regression model with interaction
lm6 <- lm(t2 ~ t1 * group, data = sim)

# visualization
plot(t2 ~ t1, data = sim)
abline(coef(lm6)[1], coef(lm6)[2])
abline(coef(lm6)[1] + coef(lm6)[3], coef(lm6)[2] + coef(lm6)[4])

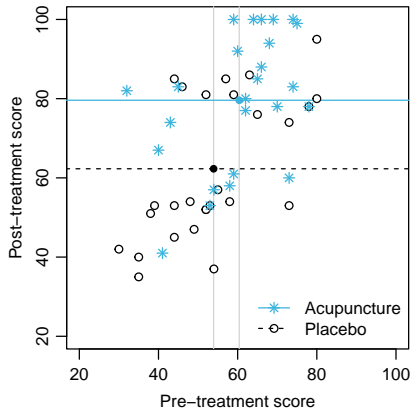
# models are nested
anova(lm4, lm5, lm6)
```

④ Example: Acupuncture for shoulder pain

Example: Acupuncture for shoulder pain

- Kleinhenz et al. (1999) investigate the effect of acupuncture on the improvement of mobility for 52 patients with shoulder pain
- Patients are randomly assigned to two groups (placebo vs. acupuncture)
- Before and after the treatment a mobility score is measured
- Vickers and Altman (2001) show advantages of an analysis of covariance compared to other methods based on these data

Acupuncture: Follow-up analysis

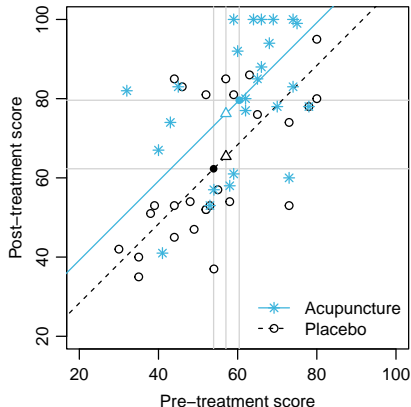


	Pla	Acu	Diff
Baseline	53.9	60.4	6.5
Follow-up	62.3	79.6	17.3
Change sc.	8.4	19.2	10.8
ANCOVA			12.7

$$y_{i2} = \beta_0 + \beta_1 x_i + \varepsilon_i$$

$$\hat{\beta}_1 = 17.3, 0.95\text{-CI: } (7.5, 27.1)$$

Acupuncture: Change score analysis

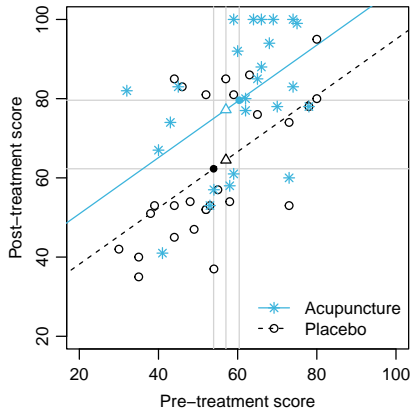


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$$y_{i2} = \beta_0 + y_{i1} + \beta_1 x_i + \varepsilon_i$$

$$\hat{\beta}_1 = 10.8, 0.95\text{-CI: } (2.3, 19.4)$$

Acupuncture: ANCOVA



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Baseline	53.9	60.4	6.5
Follow-up	62.3	79.6	17.3
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ANCOVA			12.7

$$y_{i2} = \beta_0 + \beta_1 y_{i1} + \beta_2 x_i + \varepsilon_i$$

$$\hat{\beta}_2 = 12.7, 0.95\text{-CI: } (4.1, 21.3)$$

Example: Acupuncture for shoulder pain

```
# read data
dat <- read.table("kleinhenz.txt", header = TRUE)
dat$grp <- factor(dat$grp, levels = c("plac", "acu"))

# follow-up analysis
m1 <- lm(post ~ grp, data = dat)
summary(m1)
confint(m1)

# change score analysis
m2 <- lm(post ~ offset(pre) + grp, data = dat)

# ancova
m3 <- lm(post ~ pre + grp, data = dat)
```

Example: Acupuncture for shoulder pain

```
# testing if slopes differ
m4 <- lm(post ~ pre * grp, data = dat)
anova(m3, m4)

# adjusted means
predict(m3, newdata = data.frame(pre = mean(dat$pre),
                                   grp = c("plac", "acu")))

# visualization
plot(post ~ pre, data = dat, xlim = c(20,100), ylim = c(20,100))
abline(coef(m3)[1], coef(m3)[2])
abline(coef(m3)[1] + coef(m3)[3], coef(m3)[2])
```

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or the adjusted follow-up scores which are considered to be independent

- Analysis of Covariance
 - has the highest power to detect differences for average change compared to the other methods
 - must be cautiously interpreted when groups are not randomly assigned

⑤ Linear mixed-effects model

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- Often people prefer the view of comparing the time effects within the groups instead of the adjusted follow-up scores

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- Regression notation with indicator variable for time ($t_{i1} = 0$, $t_{i2} = 1$) and group (x_i)

$$y_{ij} = \beta_0 + \beta_1 t_{ij} + \beta_2 x_i + \beta_3 (t_{ij} \cdot x_i) + v_i + \varepsilon_{ij}$$

with $v_i \sim N(0, \sigma_v^2)$ and $\varepsilon_{ij} \sim N(0, \sigma^2)$

Linear mixed-effects model

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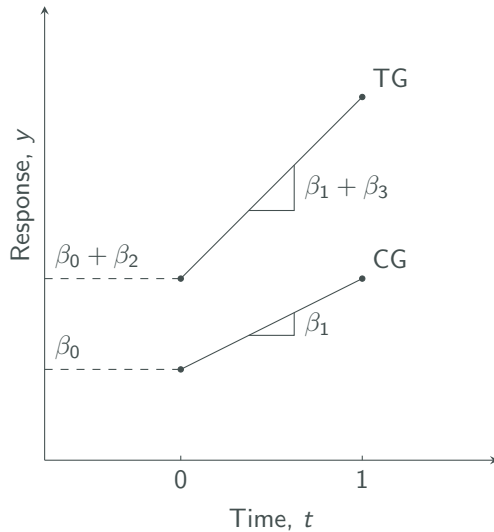
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with $v_i \sim N(0, \sigma_v^2)$ and $\varepsilon_{ij} \sim N(0, \sigma^2)$

- Interpretation:

β_0 mean baseline value in reference group
 β_1 time effect (slope) in reference group
 β_2 effect of treatment group
 β_3 effect on the slope of treatment group

Linear mixed-effects model



Linear mixed-effects model

- For the two groups with $j = 1, 2$, we get

$$y_{i1} = \beta_0 + \beta_2 x_i + v_i + \varepsilon_{i1}$$

$$y_{i2} = \beta_0 + \beta_1 + \beta_2 x_i + \beta_3 x_i + v_i + \varepsilon_{i2}$$

Linear mixed-effects model

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$$y_{i2} = \beta_0 + \beta_1 + \beta_2 x_i + \beta_3 x_i + v_i + \varepsilon_{i2}$$

- For the change score, we then get

$$y_{i2} - y_{i1} = \beta_1 + \beta_3 x_i + (\varepsilon_{i2} - \varepsilon_{i1})$$

Linear mixed-effects model

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$$y_{i1} = \beta_0 + \beta_2 x_i + v_i + \varepsilon_{i1}$$

$$y_{i2} = \beta_0 + \beta_1 + \beta_2 x_i + \beta_3 x_i + v_i + \varepsilon_{i2}$$

- For the change score, we then get

$$y_{i2} - y_{i1} = \beta_1 + \beta_3 x_i + (\varepsilon_{i2} - \varepsilon_{i1})$$

- Since ε_{ij} are independent, this results in the equation for the change score analysis

$$y_{i2} - y_{i1} = \beta_1 + \beta_3 x_i + \varepsilon_i$$

with

$$\varepsilon_i = \varepsilon_{i2} - \varepsilon_{i1} \sim N(0, \sigma_d^2 = 2\sigma^2)$$

Linear mixed-effects model

- For the two groups with $j = 1, 2$, we get

$$y_{i1} = \beta_0 + \beta_2 x_i + v_i + \varepsilon_{i1}$$

$$y_{i2} = \beta_0 + \beta_1 + \beta_2 x_i + \beta_3 x_i + v_i + \varepsilon_{i2}$$

- For the change score, we then get

$$y_{i2} - y_{i1} = \beta_1 + \beta_3 x_i + (\varepsilon_{i2} - \varepsilon_{i1})$$

- Since ε_{ij} are independent, this results in the equation for the change score analysis

$$y_{i2} - y_{i1} = \beta_1 + \beta_3 x_i + \varepsilon_i$$

with

$$\varepsilon_i = \varepsilon_{i2} - \varepsilon_{i1} \sim N(0, \sigma_d^2 = 2\sigma^2)$$

→ LMM for two time points is equivalent to change score analysis!

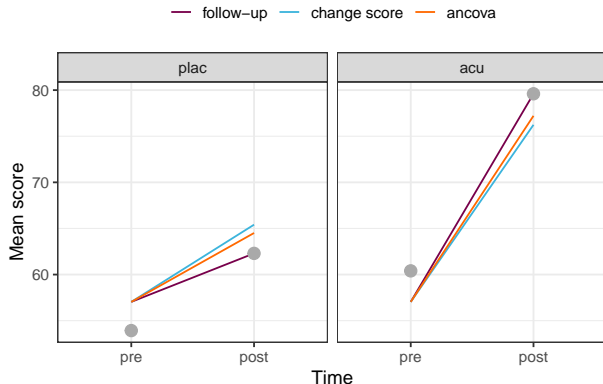
Example: Acupuncture for shoulder pain

```
# read data
dat <- read.table("kleinhenz.txt", header = TRUE)
dat$grp <- factor(dat$grp, levels = c("plac", "acu"))

# change score analysis
m1 <- lm(post ~ offset(pre) + grp, data = dat)
# LMM
dat1 <- reshape(dat, direction = "long",
                varying = list(1:2), v.names = "score")
dat1$time <- factor(dat1$time, levels = 1:2, labels = c("pre", "post"))
m2 <- lmer(score ~ grp * time + (1 | id), data = dat1)
# compare residual variances
sigma(m1)^2
2 * sigma(m2)^2
```

“Adjusted” time effects

- The ANCOVA model will give you adjusted time effects within the groups with a little reparametrization



```
m5 <- lm(post - pre ~ scale(pre) + grp, data = dat)
predict(m5, data.frame(pre = mean(dat$pre), grp = c("plac", "acu"))))
```

References

- Kleinhenz, J., Streitberger, K., Windeler, J., Güßbacher, A., Mavridis, G., & Martin, E. (1999). Randomised clinical trial comparing the effects of acupuncture and a newly designed placebo needle in rotator cuff tendinitis. *Pain*, 83(2), 235–241.
- Vickers, A. J., & Altman, D. G. (2001). Analysing controlled trials with baseline and follow up measurements. *BMJ*, 323(7321), 1123–1124.