Grease the gears: how lubrication of syringe pumps impacts microfluidic flow precision

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SUPPLEMENTARY INFORMATION

Lubrication of the syringe pump

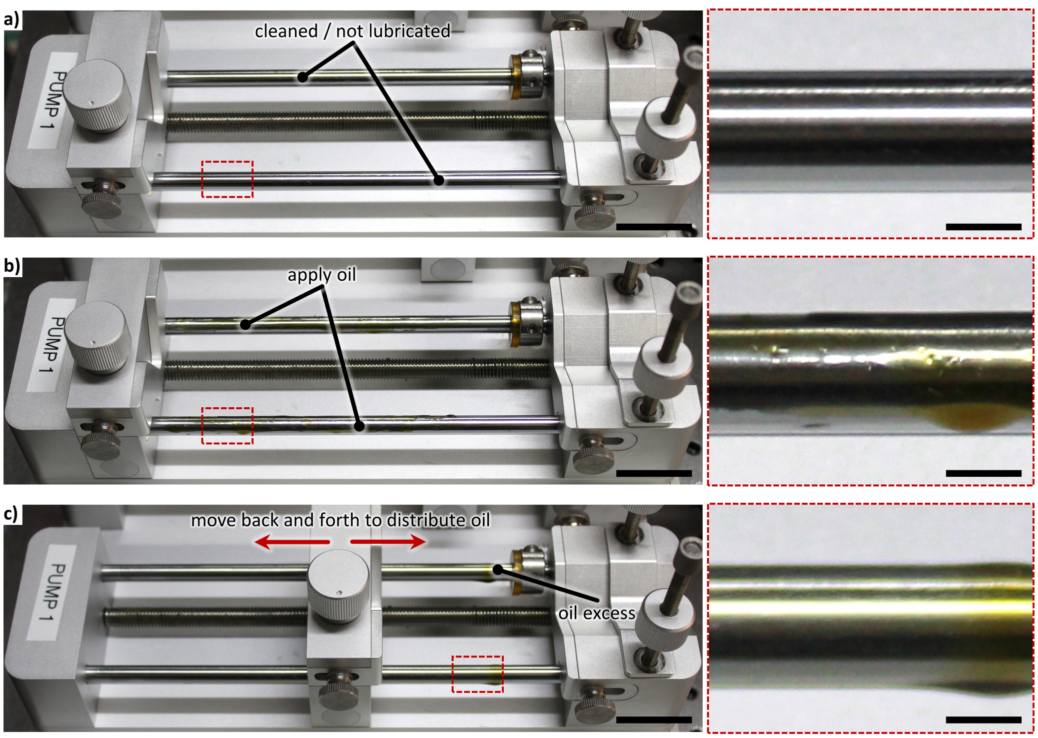

Figure S1 Images from the lubrication process. The red dashed boxes in the left images (scale bars equal 3 cm) are shown magnified to the right (scale bars equal 0.5 cm). a) The guide rods of the syringe pump were cleaned with no remaining oil. b) Oil was applied to the guide rods with a small brush. The drive screw could be lubricated, too, in the same way to minimize wear. c) Moving the pusher block slowly back and forth distributes the oil along the guide rods and allows creeping into the fit. Excess oil can be reapplied on the guide rods or carefully removed with a soft wipe.

Plastic 5 mL syringe

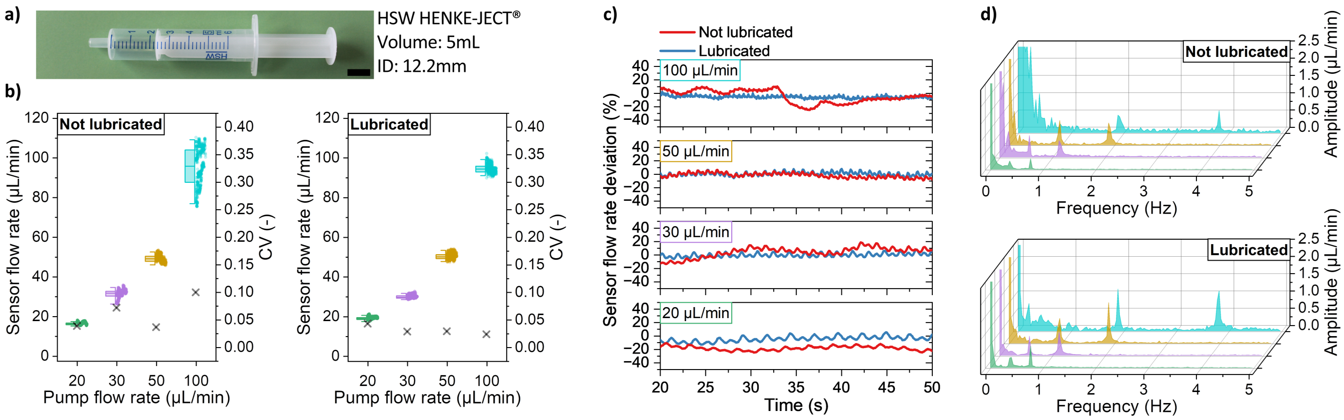

Figure S2 Quantitative analysis of the flow rate stability for lubricated and not-lubricated guide rods with a plastic syringe and colour-coded flow rates ranging from 20 to 100 µL min^{-1}. a) shows the 5 mL plastic syringe with a 12.2 mm inner diameter. The scale bar equals 1cm. b) The flow profiles were evaluated between 20–50 s and plotted with whiskers at the 2.5 and 97.5 percentile of the data. The data's coefficient of variation (CV) is plotted with black crosses (*x*) on the right *y*-axis. Lubrication reduces the CV significantly. c) Comparison of the lubricated and not-lubricated flow profiles that are normalized to their respective specified flow rate. d) shows the flow profiles between 20–50 s in the frequency domain by FFT for the not-lubricated and lubricated syringe pumps, respectively.

Withdrawing with the 2500 µL glass syringe

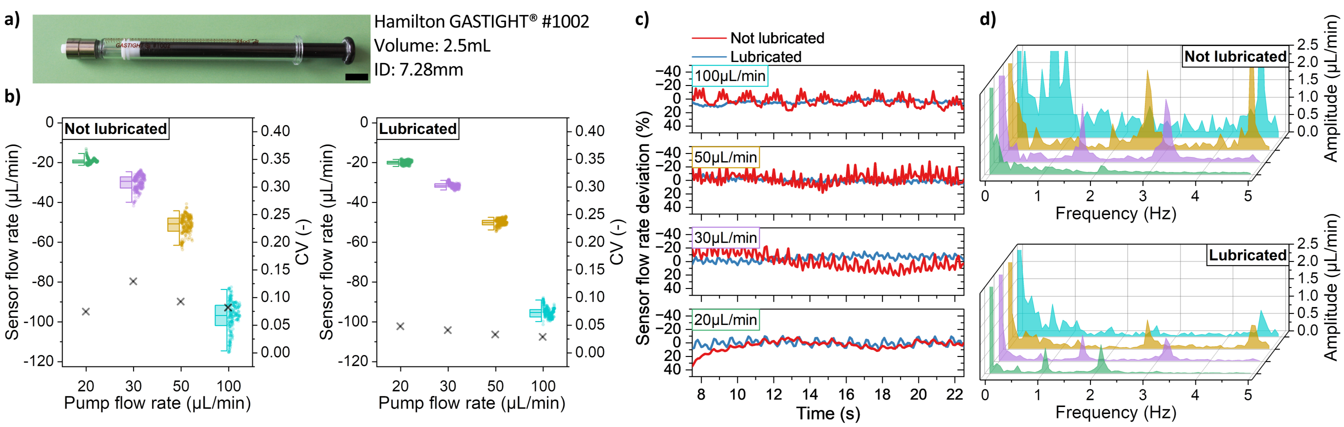

Figure S3 Quantitative analysis of the flow rate stability when withdrawing for lubricated and not-lubricated guide rods with a glass syringe and colour-coded flow rates ranging from 20 to 100 µL min^{-1}. a) shows the 2500 µL glass syringe with a 7.28 mm inner diameter. The scale bar equals 1 cm. b) The flow profiles were evaluated between 7.5–22.5 s and plotted with whiskers at the 2.5 and 97.5 percentile of the data. The data's coefficient of variation (CV) is plotted with black crosses (*x*) on the right *y*-axis. Lubrication reduces the CV significantly. c) Comparison of the lubricated and not-lubricated flow profiles that are normalized to their respective specified flow rate. d) shows the flow profiles between 7.5–22.5 s in the frequency domain by FFT for the not-lubricated and lubricated syringe pumps, respectively.

Flow profiles from glass syringes in infusion and withdrawal mode

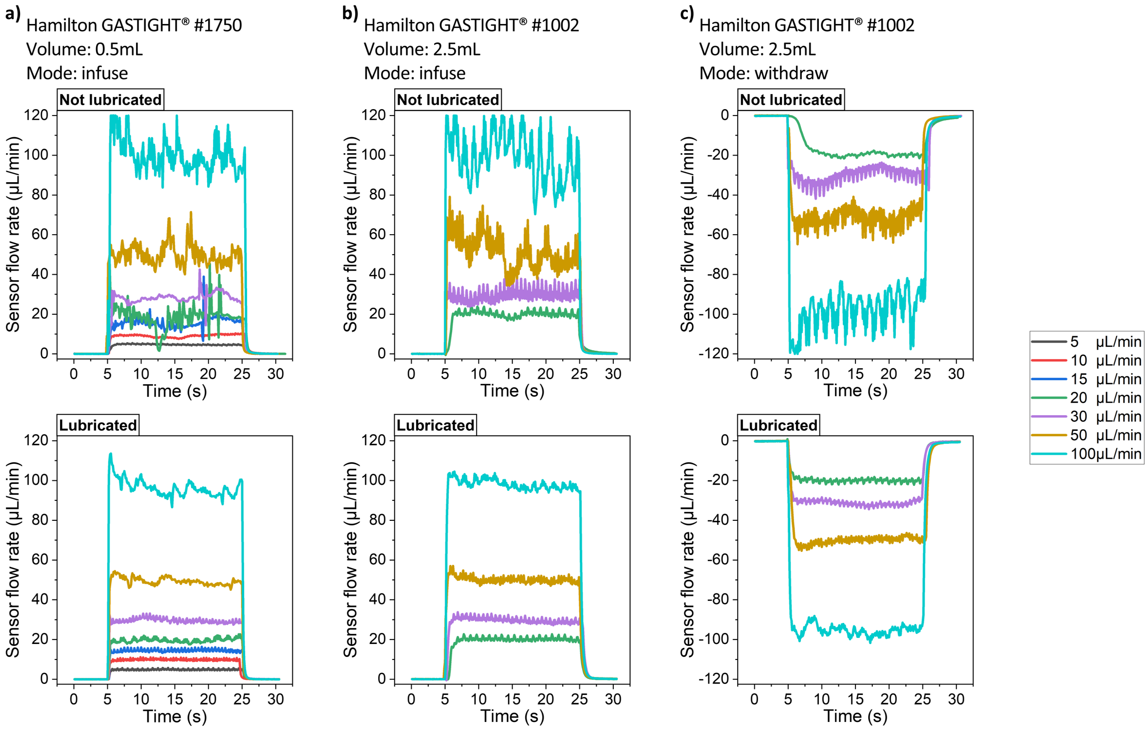

Figure S4 Dynamic flow rates for not-lubricated and lubricated guide rods of glass syringes with (a) 0.5 mL volume in infusion mode, (b) 2.5 mL volume in infusion mode, and (c) 2.5 mL volume in withdrawal mode.

Flow profiles from plastic syringes in infusion mode

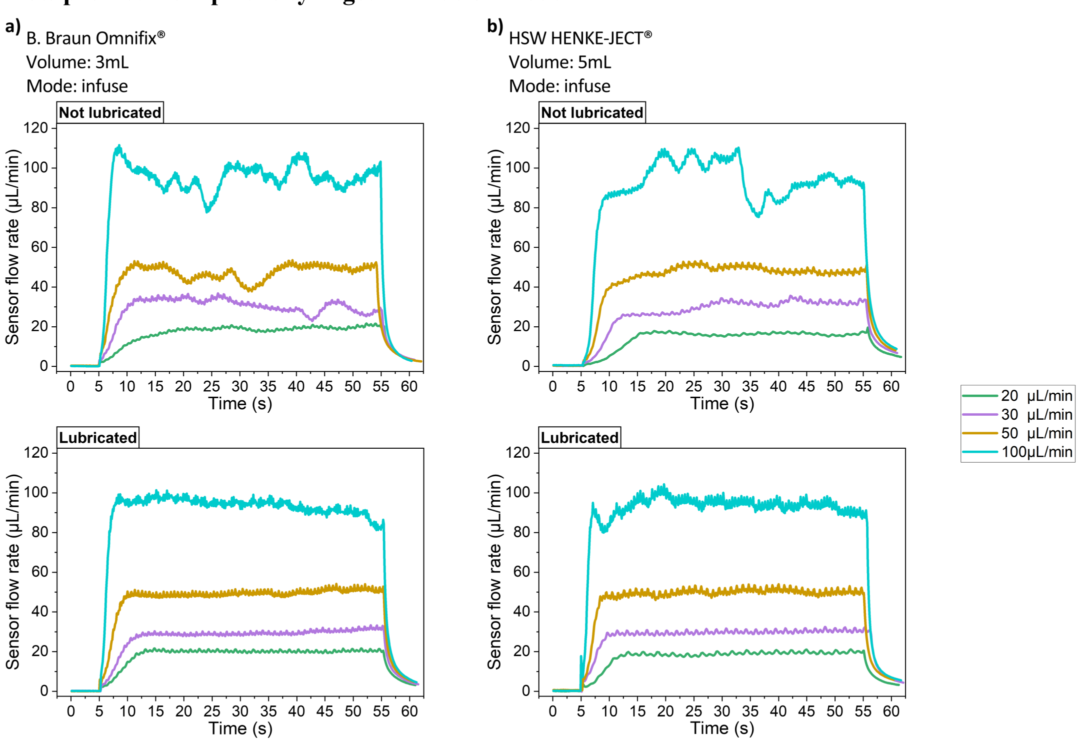

Figure S5 Dynamic flow rates for not-lubricated and lubricated guide rods of glass syringes with (a) 3 mL volume and (b) 5 mL volume, both in infusion mode.

Oscillating flow rates from dripping outlet

In addition to the flow rate fluctuations induced by poor lubrication of the guide rods, we set these fluctuations in context with oscillations from a dripping outlet to descriptively show their similarities and highlight the relevance of an immersed outlet. For measurements with a dripping outlet, the end of the tube was positioned horizontally into the air and not into a pre-filled Eppendorf tube. The guide rods were lubricated, and all other settings were kept the same as for the 500 µL glass syringe.

If the outlet tubing end was not immersed in the water, drops formed at the outlet and dripped off when reaching a critical size. An oscillating flow was observed, especially for flow rates smaller than 15 µL min^{-1} (Fig. S6). The measured flow rate pattern started with a distinct peak towards higher flow rates, followed by a peak in the opposite direction. The rising peak originated from the drop falling off the tube and pulling water out, while the falling peak, most often significantly flatter, resulted from refilling the deficit. With increasing flow rates, the dripping and oscillation frequencies also increased until a steady, low volatile flow rate was established for flow rates above 20 µL min^{-1} with CV values below 0.05. In this way, the inward and outward flux of the oscillation overlapped and compensated dripping effects. It is essential to mention that the oscillating flow rates highly depend on the liquid-solid and liquid-fluid interface of the drop, its surroundings, and the tube or outlet geometry. The deviations from the expected flow rate can be quantified as similarly significant but more predictable, like those from a canting pusher block. The different components are broken down in the frequency spectrum with distinct contributions for flow rates from 5–15 µL min^{-1}. The dripping frequency for the 5 µL min^{-1}, 10 µL min^{-1}, and 15 µL min^{-1} flow rates can be determined to be 0.53 Hz, 1.06 Hz, and 1.32 Hz, respectively. Since the flow rates of 20–30 µL min^{-1} produce a continuous flow rather than single drops, they exhibit mainly additional background noise in the frequency spectrum overlayed with the same frequencies from mechanical vibrations found for the lubricated guide rods.

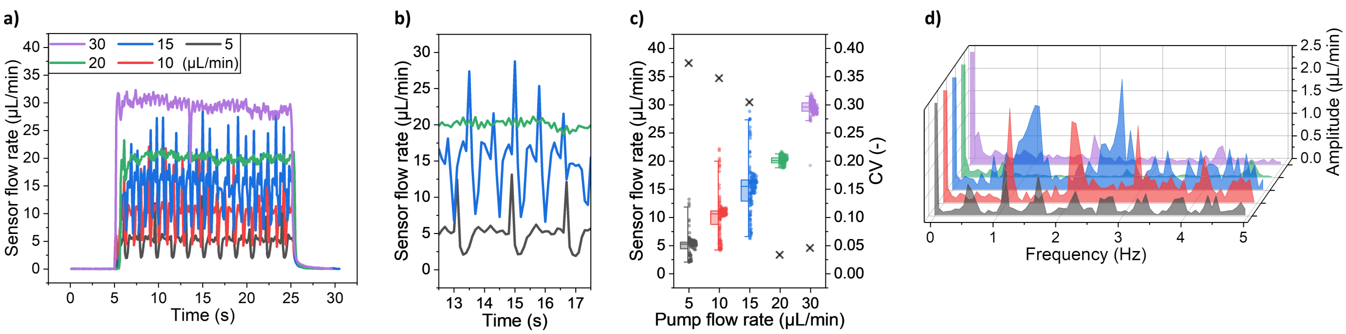

Figure S6 Dynamic colour-coded flow rate profiles are shown in a) and b). c) The quantitative analysis of the flow rate stability for an outlet tubing not ending in a reservoir but dripping. The flow rates between 7.5–22.5s were evaluated and plotted with whiskers at the 2.5 and 97.5 percentile of the data. The data's coefficient of variation (CV) is plotted with black crosses (x) on the right y-axis. d) shows the flow profiles between 7.5–22.5s in the frequency domain by FFT for the outlet tubing not ending in a reservoir.